supplemental information for

Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase

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S1 Supplemental Models

To compare with prior work that used a fixed fraction of the growing season prior to harvest to assess temperature sensitivity [1], we fix the development period across years by taking the mean of the weights for each state, $P_{p,d}$, and applying those to all years (Fig. 1). Whereas early grain filling clearly remains the most sensitive phase, late grain filling estimates are almost entirely different - indicating a negative sensitivity across much of the corn belt and sometimes a positive response to KDDs (Fig. S5). This result is unsupported by any biological explanation and, apparently, arises from incorrectly sampling the weather actually associated with late grain filling. Given that there is also a trend toward earlier planting [2] which has the effect, when the seasons are fixed, of shifting actual late grain filling dates into what is defined as the drydown phase this has likely contributed to confused sensitivity estimates under fixed development dates.

As the drydown phase represents a period where the crop is no longer biologially active we construct an alternative model which omits this phase and focuses only on the vegetative, early grain filling, and late grain filling phases (Fig. S6). The parameter estimates are largely unchanged, and given that grains are still vulnerable until harvest we prefer the model which includes the drydown phase. Note that incorporating the drydown phase as part of the late grain filling phase may bias the parameter estimates on account of the substantial differences between the two.

S2 Supplemental Tables

State	Veg. [G]	EGF [G]	LGF [G]	Dry. [G]	Veg. [K]	EGF. [K]	LGF [K]	Dry. [K]	WS [G]	WS [K]
Georgia	2.5	1.6	2.3	-1.3	-6.4	-9.1	-9.6	2.7	1.6	-7.8
Illinois	0.0	-1.5	3.6	8.7	1.0	-47	-2.2	-8.8	4.9	-14
Indiana	-2.8	4.1	2.3	7.6	-10	-41	2.1	-10	4.6	-15
Iowa	1.0	-10	13	4.2	-0.5	-14	-20	-18	6.5	-13
Kansas	-1.6	7.5	6.1	5.1	-5.7	-18	-13	12	2.8	-9.6
Kentucky	1.8	9.5	3.8	5.6	-3.1	-34	1.0	-9.7	3.7	-10
Michigan	-4.2	6.7	9.5	1.6	-1.2	-35	-20	24	3.9	-13
Minnesota	1.0	3.4	15	4.7	-1.8	-18	-38	16	6.8	-13
Missouri	2.4	11	6.0	5.7	2.6	-42	-5.7	-5.5	5.5	-12
Nebraska	-0.6	11	10	2.2	-4.6	-25	-3.5	-16	6.1	-11
North Carolina	-2.2	3.5	2.7	2.1	-13	-21	-11	-2.2	0	-12
Ohio	-1.6	-3.0	3.8	6.1	-7.3	-26	-20	34	3.6	-15
Pennsylvania	2.4	9.4	1.0	8.9	-9.9	-31	-20	17	5.3	-18
South Dakota	3.4	-0.6	5.5	8.3	-8.1	-11	-19	7.3	5.7	-11
Texas	3.2	-2.6	-6.0	-0.9	-17	0.5	5.7	-6.6	-3.1	-4.6
Wisconsin	-2.0	5.0	9.4	5.0	-1.7	-27	-49	57	5.8	-17

Table S1: Yield sensitivity to growing degree days [G] and killing degree days [K] broken down by growth phase: Veg. for Vegetative, EGF for Early Grain Filling, LGF for Late Grain Filling, Dry. for Drydown, and over the whole growing season [WS]. Units are (kg/ha)/(°C day).

State	Veg. [G]	EGF [G]	LGF [G]	Dry. [G]	Veg. [K]	EGF [K]	LGF [K]	Dry. [K]	WS [G]	WS [K]
Georgia	890	400	550	280	110	100	130	40	2120	380
Illinois	780	310	480	230	60	40	50	10	1800	160
Indiana	790	300	460	240	60	30	40	10	1780	140
Iowa	800	330	330	220	50	30	20	10	1670	110
Kansas	860	350	490	250	90	80	110	30	1940	310
Kentucky	840	370	440	270	80	70	70	20	1920	240
Michigan	730	320	310	150	30	20	10	0	1500	60
Minnesota	730	330	310	140	40	20	10	0	1520	80
Missouri	800	300	480	250	60	50	80	20	1840	210
Nebraska	850	310	490	210	90	50	60	10	1870	220
North Carolina	870	360	520	340	80	70	90	30	2090	260
Ohio	780	270	460	190	50	20	20	0	1700	100
Pennsylvania	800	290	410	160	60	30	20	0	1650	110
South Dakota	790	240	340	170	70	30	30	10	1540	150
Texas	1080	410	600	270	170	130	210	80	2350	590
Wisconsin	740	280	310	140	30	10	10	0	1470	60

Table S2: The planting area weighted mean growing [G] and killing [K] degree days in each state and growing phase: Veg. for Vegetative, EGF for Early Grain Filling, LGF for Late Grain Filling, Dry. for Drydown. As well as summed over the whole season [WS]. All values are in units of (°C day) and rounded to the nearest ten.

S3 Supplemental Figures

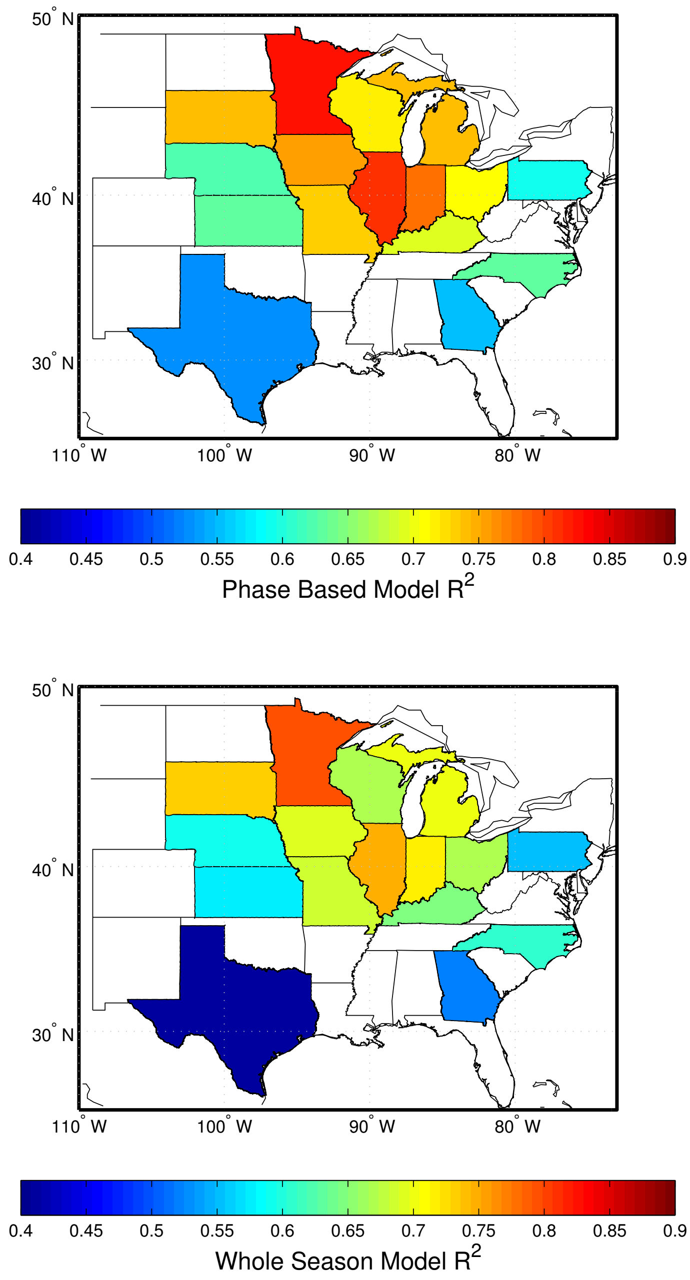

Figure S1: **Correlation between observed and predicted yields.** (top) Squared cross-correlation between developmentally-resolved model predictions and observations of yield, and (bottom) between whole-season model prediction and yield. In all cases, the more resolved model gives a slightly higher correlation, as follows from the greater degrees of freedom.

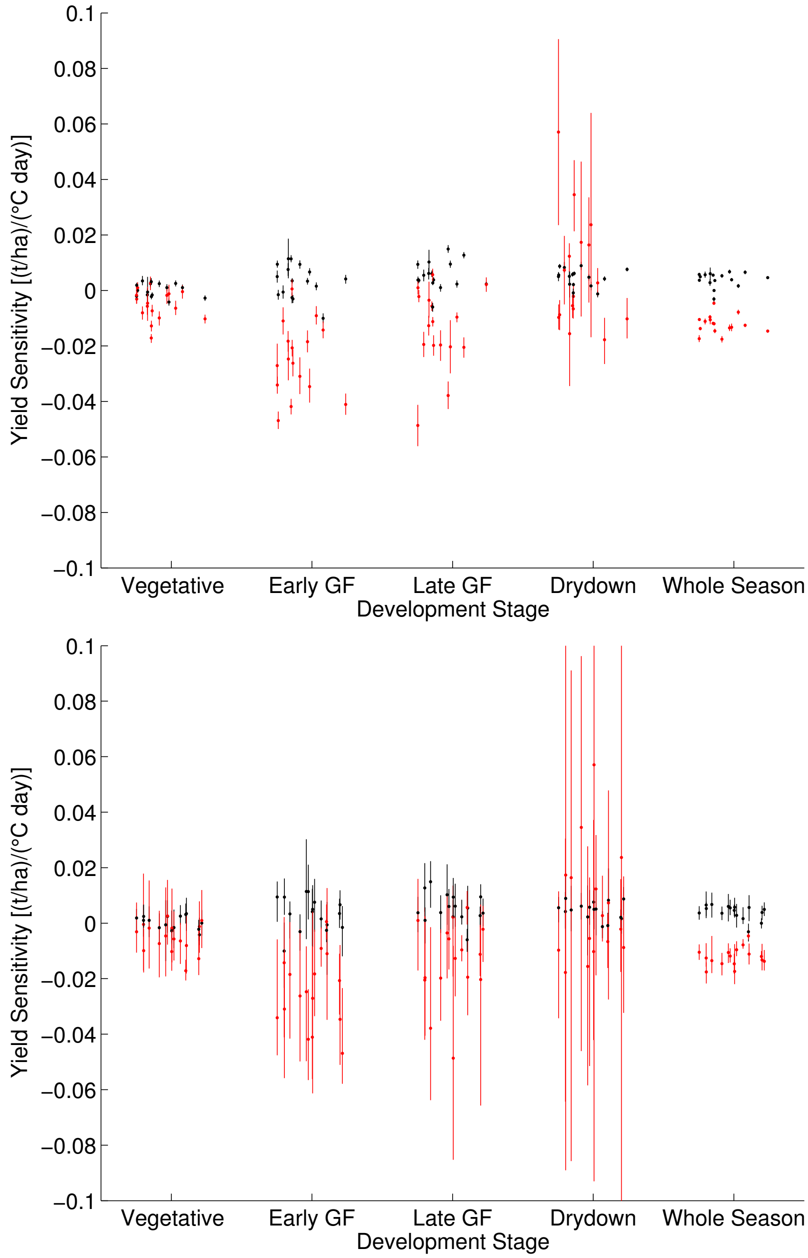

Figure S2: **Confidence intervals calculated using state-level and county-level aggregation.** (top) Yield sensitivity for GDDs (black) and KDDs (red) for each stage and whole-season values, where spacing along the x-axis is purely for visual purposes. Vertical bars indicate the 95% confidence level, and are obtained through a bootstrapping procedure where data is resampled at the county level according to year. This approach assumes that county-level data is independent. (bottom) In order to account for spatial dependence, uncertainties are also estimated using a block-bootstrap procedure where yields are resampled according to year at the state level. In this case, there are fewer degrees of freedom permitted for estimation, leading to larger variance in the result. Actual uncertainties are expected to reside between these two end-member cases. Note that in either case the early and late grain filling phases — which we focus on — have the most clearly distinct KDD and GDD sensitivity estimates. GF indicates the grain filling stages.

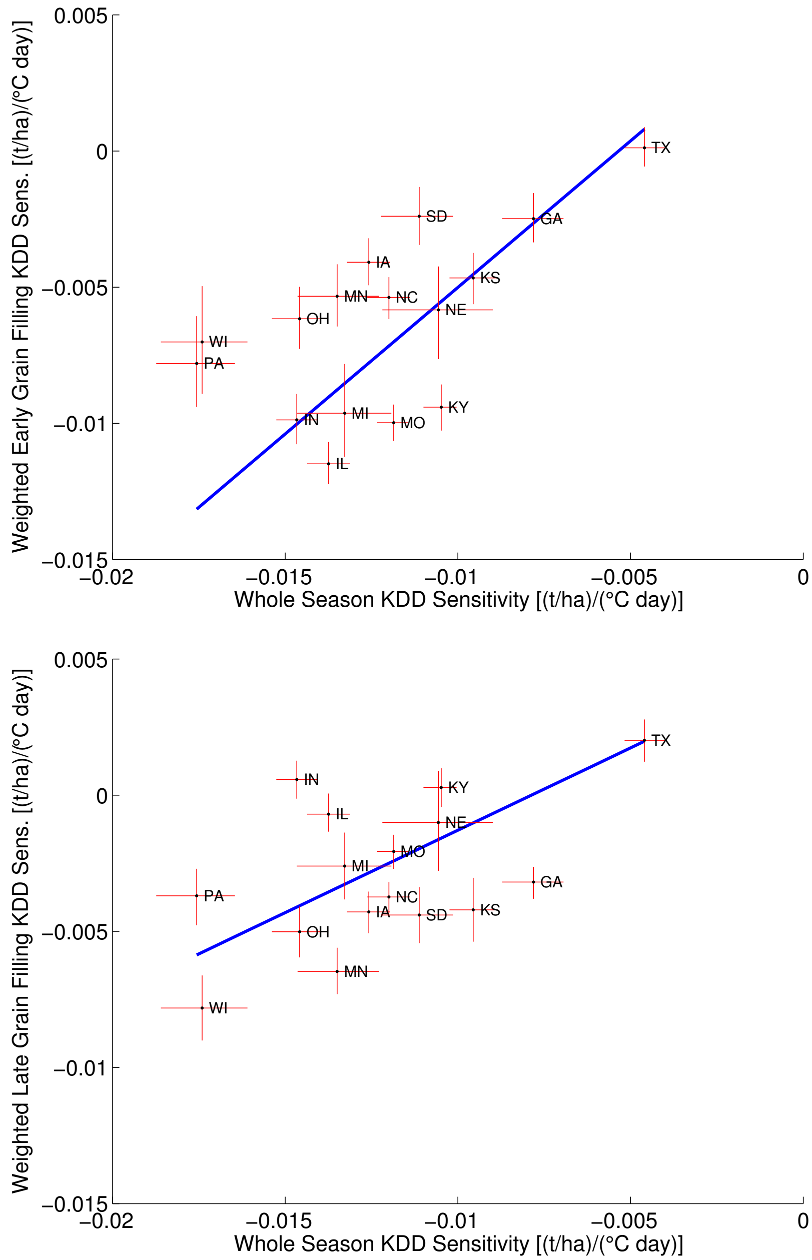

Figure S3: **Relationship between grain filling sensitivity and whole season sensitivity to KDDs**. The red crosses associated with each state are the respective 95% confidence intervals for the sensitivity estimates. top) The R^2 between weighted early grain filling and whole season KDD sensitivity is 0.37 and the York fit slope is nearly 1.1. bottom) The R^2 between weighted late grain filling and whole season KDD sensitivity is 0.27 and the York fit slope is 0.61. This indicates that variations in both grain filling sensitivities are, on the whole, an important driver of the entire variation in whole season sensitivity.

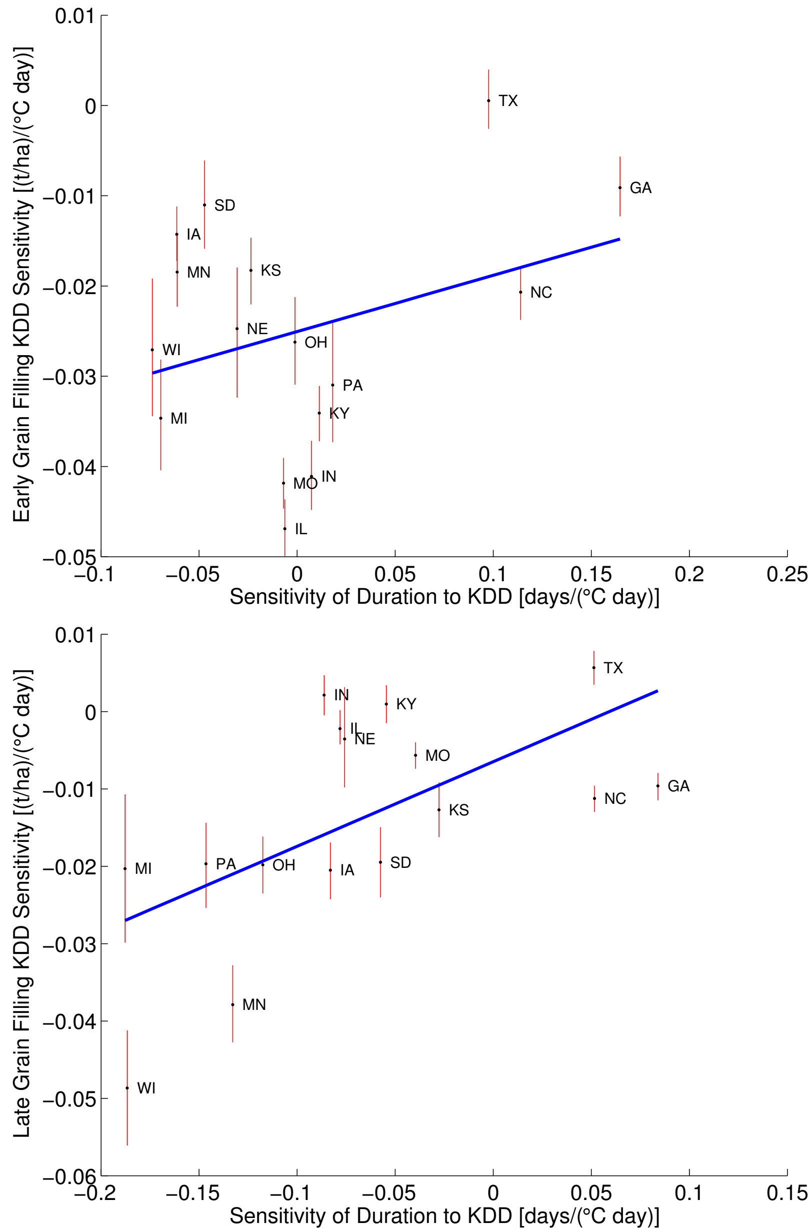

Figure S4: **Relationship between KDD sensitivity and duration of grain filling** Vertical red lines are the 95% confidence interval associated with each sensitivity. top) The relationship between early grain filling rate per KDD and sensitivity provides some indication of adaptation, but the fit is not particularly strong, with an R^2 of 0.1. bottom) The relationship between late grain filling rate per KDD and sensitivity provides further evidence of a physiological basis for latitudinal adaptation. The linear fit, in blue, fits the data with an R^2 of 0.36.

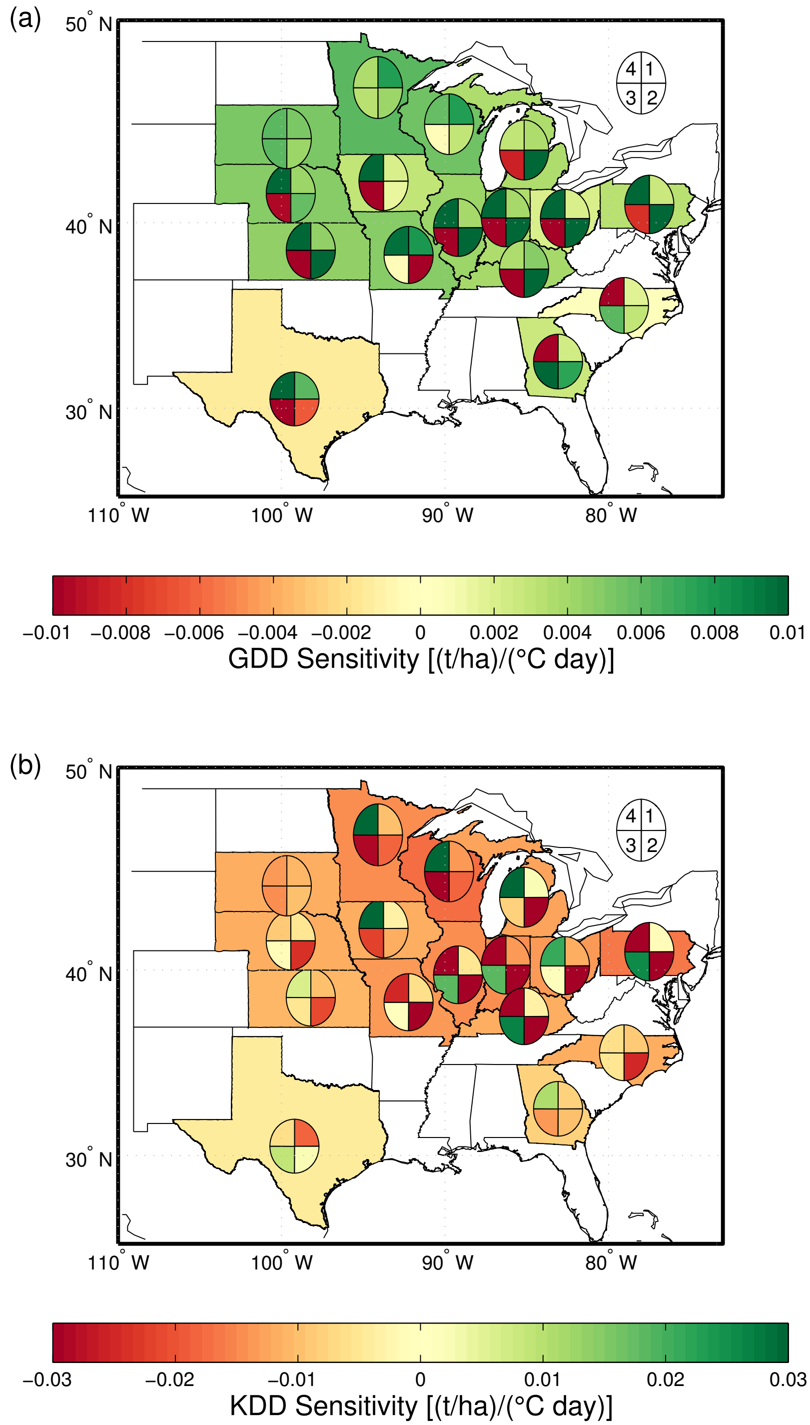

Figure S5: **GDD and KDD Sensitivity with fixed growing season.** (a) When growing stage dates are fixed to average state-wide values, many states exhibit a negative relationship between GDD and yield during late grain filling, and a strong positive relationship betweeen GDD and yield during the drydown phase of development. (b) KDD sensitivity is also counter-intuitive, with high temperatures during late grain filling generally indicated as beneficial. These results indicate the importance of correctly specifying phase dates when attempting a more resolved analysis of sensitivity.

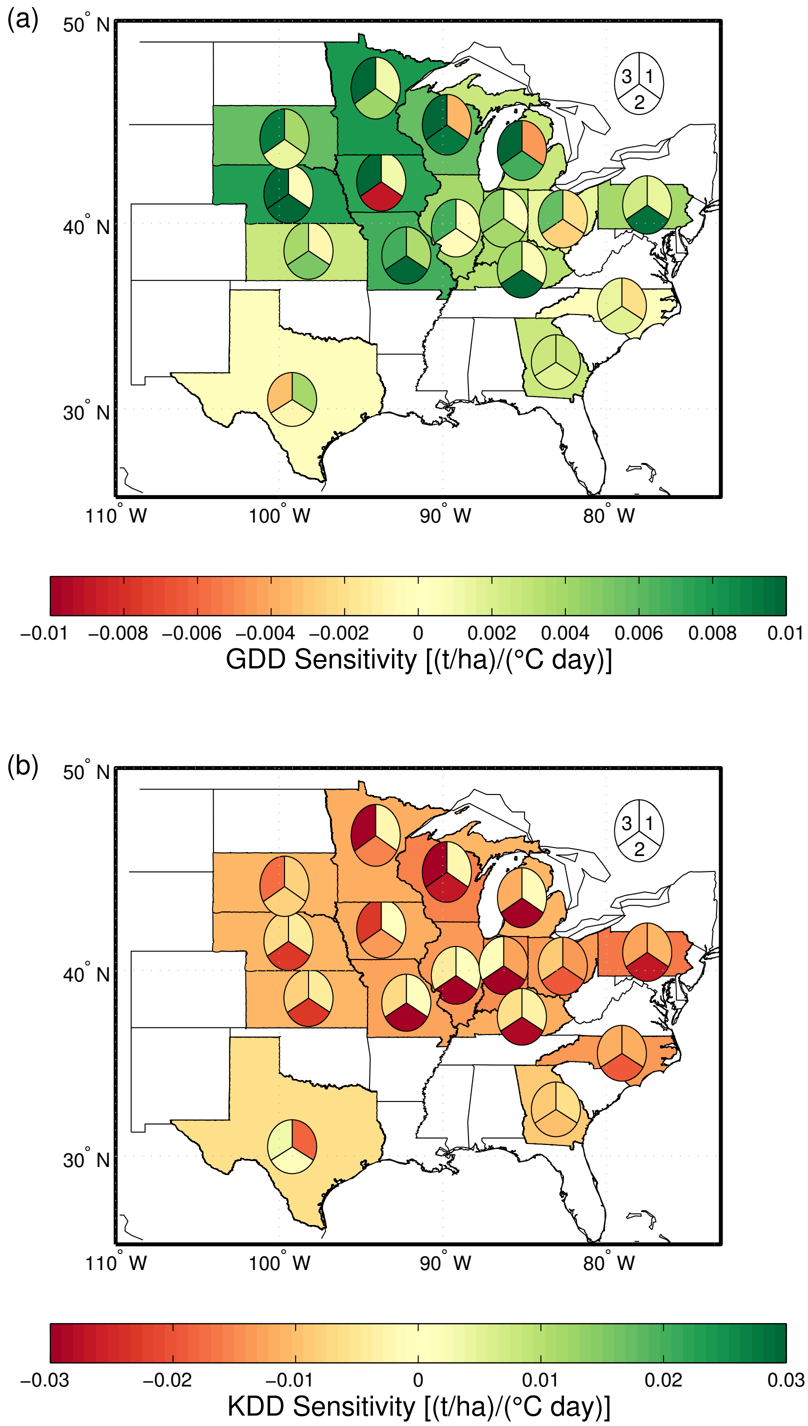

Figure S6: **GDD and KDD Sensitivity without a drydown phase.** (a) GDD sensitivity estimates and (b) KDD sensitivity estimates are largely unchanged when the drydown phase is omitted from the analysis.

References

[1] S.M. Gourdji, A.M. Sibley, and D.B. Lobell. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future predictions. *Environ. Res. Lett.*, 8:10pp, 2013.

[2] C.J Kucharik. A multidecadal trend of earlier corn planting in the central usa. *Agron. J.*, 98:1544–1550, 2006.