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Supplement of

Quantifying the impacts of compound extremes on agriculture

Iman Haqiqi et al.

Correspondence to: Iman Haqiqi (ihaqiqi@purdue.edu)

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S.1. Overview

This material provides details on the soil moisture module, estimation strategy, decomposition method, and some robustness checks on the results and the model variables. Besides, this material illustrates the correlation between mean volumetric soil moisture and other potential seasonal variables that can be used as indicators of water availability. This includes cumulative precipitation, mean seasonal evapotranspiration, and mean seasonal soil moisture. It also provides some examples to demonstrate the seasonal mean soil moisture shows no linear relationship with the seasonal heat index (dday 10˚C). However, it has a positive correlation with evapotranspiration and soil moisture fraction. Then alternative models are introduced controlling for irrigation, growth periods, spatial scope of the study, and other measures of individual and compound extremes.

S.2. Soil moisture in the Water Balance Model

Here, we briefly describe WBM's soil moisture module. However, the model is much more complex and employs a large list of inputs. Full documentation for WBM can be found in Wisser et al., (2010) with updates in Grogan (2016). In WBM, crop-specific soil moisture balance within each grid cell is calculated with an accounting system that tracks a location's water inputs and outputs and is limited by the soil moisture pool's water holding capacity.

$$\frac{\delta W_s}{\delta t} = \begin{cases} g(Ws)(I - PET)\ if\ I < PET \\ I - PET\ if\ PET\ \leq I\ and\ (I - PET) < (W_{cap} - W_s) \\ W_{cap} - W_s\ if\ PET\ \leq I\ and\ \left(W_{cap} - W_s\right) \leq (I - PET) \end{cases} \qquad \text{(s1)}$$

where W_s is soil moisture, t is time, I is the sum of all water inputs to the soil moisture pool, PET is potential evapotranspiration, and W_{cap} is available water capacity. Water inputs to the soil come in the form of precipitation as rain and as snowmelt. Water intercepted by the canopy reduces precipitation reaching the soil. Here, we use the Hamon method for estimating PET (Federer et al., 1996; Hamon, 1963), and $g(W_s)$ is 1 for all crops, while it is an exponential function of soil moisture depth for non-crop soil areas. Crop-specific potential evapotranspiration values, $PETc$, are calculated following the FAO-recommended crop-modeling methodology (Allen et al., 1998):

$$PET_c = k_c \cdot PET \qquad \text{(s2)}$$

where k_c [-] is a crop-specific, time-varying scalar. Crop scalar values are from Siebert and Döll (2010), and crop maps that identify the area of each rainfed crop type within a grid cell are from the Cropland Data Layer. When soil moisture is insufficient for crops to extract water equal to PET_c, actual crop evapotranspiration is limited to available soil water volumes. Available water capacity, W_{cap}, is a function of vegetation-specific rooting depth, a crop-specific depletion factor, soil field capacity, and soil wilting point:

$$W_{cap} = D_c R_c (F - W_p) \qquad \text{(s3)}$$

where D_c is the depletion factor for crop c, R_c is the rooting depth of crop c, F is the soil field capacity, and W_p is the soil wilting point. Here we use the Harmonized World Soil Database (Fischer et al., 2008) as model input for all soil properties. Corn rooting depth is set to 1 meter; and the depletion factor is 0.5, following Siebert and Döll (2010). Once the soil moisture content reaches field capacity, no further water is added to the soil moisture pool; excess inputs move to the groundwater pool via percolation and the river system via runoff.

S.3. Estimation strategy

Considering the exposure to each temperature interval to capture the marginal impact of heat and water on crop yields, we estimate the following for Model (1-a):

$$y_{it} = \alpha D_{it}^{10-29} + \beta D_{it}^{29} + \delta_a P_{it} + \delta_a' P_{it}^2 + \lambda_s t + \lambda_s' t^2 + c_i + \varepsilon_{it} \qquad \text{(s4)}$$

where i is an index for counties, t is the index of time, s is the index for states, y_{it} is the log corn yields, D_{it} represents growing degree day variables, P shows cumulative precipitation over the growing season, t shows the time trend variable (t = year – 1950), c_i is a time-invariant county fixed effect, ε is the residual, and $\alpha, \beta, \delta, \lambda$ are the regression parameters showing the marginal impacts. The subscript a is used to show the water coefficients (δ) are related to metrics in Model (1-a). To evaluate the importance of soil moisture metrics in Model (1-b), we estimate the following:

$$y_{it} = \alpha D_{it}^{10-29} + \beta D_{it}^{29} + \delta_b M_{it} + \delta_b' M_{it}^2 + \lambda_s t + \lambda_s' t^2 + c_i + \varepsilon_{it} \qquad \text{(s5)}$$

where the variables are defined as Model (1-a) except for the water availability metric. Here M shows the seasonal mean soil moisture index calculated as average daily root zone soil moisture from the first day of April to the end of September. The subscript b is used for δ to distinguish the water coefficients in Model (1-b). For Model (1-c) we estimate the following model:

$$y_{it} = \alpha D_{it}^{10-29} + \beta D_{it}^{29} + \delta_c NDD_{it}^{def} + \delta_c' NDS_{it}^{sur} + \lambda_s t + \lambda_s' t^2 + c_i + \varepsilon_{it} \qquad \text{(s6)}$$

where we replace seasonal mean or cumulative metrics with two new metrics to control the impacts of water extremes on corn yields. Here, NDD^{def} is the number of days that soil moisture is under 25 mm below normal levels (deficit); and NDS^{sur} is the number of days that soil moisture is higher than 25 mm above normal levels. The rest of the variables are defined as Model (1-a). The subscript c shows δ_c is specific to Model (1-c). Finally, we estimate the following equation for Model (1-d):

$$y_{it} = \alpha D_{it}^{10-29} + \beta D_{it}^{29} + \delta_d CMS_{it} + \delta_d' CMD_{it} + \lambda_s t + \lambda_s' t^2 + c_i + \varepsilon_{it} \qquad \text{(s7)}$$

where *CMS* is a cumulative measure of positive soil moisture deviations compared to the normal levels (equivalent to A+B+C in Fig. 1). And *CMD* is the cumulative measure of negative soil moisture deviations compared to the normal levels (equivalent to D+E+F in Fig. 1). The subscript d distinguished estimated δ from previous models.

We assume the errors are serially correlated due to unobservable and systematic measurement errors, and we consider clustering US counties by the state which has been a standard approach in the literature (Blanc and Schlenker, 2017; Hsiang, 2016; Lobell and Burke, 2010). In this study, the models are estimated using a panel fixed-effect approach. A panel fixed-effect approach is a statistical method for analyzing two-dimensional (e.g. time and location) panel data. This method is helpful for analyzing those data collected for the same locations over time with a relatively short time span (Wooldridge, 2016). As our data set contains information for counties over time, a panel data analysis is appropriate. In addition, a fixed-effect model is appropriate as there are unique biophysical and economic attributes of counties that can explain yield differences across counties and are not changing over time. When we conduct a statistical test (Hausman test), it rejects the random effects model in favor of the fixed effect models we use. The panel consists of 35 years (1981-2015) for all US counties with corn production. For purposes of model comparison, we provide adjusted R^2, Akaike's information criterion (AIC), and Bayesian information criterion (BIC).

For Model (2), we consider the daily interaction of heat and soil moisture as the compound metric. The interaction term is defined when the marginal impact of an explanatory variable depends on the magnitude of yet another explanatory variable (Wooldridge, 2016). Here, the marginal impact of heat on yield depends on water availability; also, the marginal impact of water on yield depends on heat. This is called conditional marginal impact. A key empirical challenge arises when estimating the model with daily interaction of heat and soil moisture. A simple multiplicative interaction of soil moisture variable and heat variables will be problematic (Hainmueller et al., 2019). It implies a linear interaction effect that changes at a constant rate with heat. However, as will be shown below, soil moisture has a non-linear marginal effect. We take two approaches here to calculate the conditional marginal impact of heat on corn yields to address the challenges of aggregating daily soil moisture to seasonal water availability metrics. Model (2-a) provides the conditional marginal impact of excess heat as:

$$y_{it} = \alpha D_{it}^{10-29} + \left\{ \sum_m \beta_m D_{mit}^{29} \right\} + \delta M_{it} + \delta' M_{it}^2 + \lambda_s t + \lambda_s' t^2 + c_i + \varepsilon_{it} \tag{s8}$$

where i is the county index, t is the time index, m is an index of soil moisture condition (high, low, normal), s is an index for states, y is average corn yields, D represents conditional growing degree day variables, M shows the seasonal mean soil moisture content, T stands for the time trend variable, c_i is a time-invariant county fixed effect. Here, β is indexed by m; i.e., the marginal impact of heat is conditional to soil moisture conditions. $\alpha, \beta, \delta, \lambda$ are the regression parameters showing the marginal impacts.

Second, we estimate a model with metrics of soil moisture while controlling for temperature in Model (2-b). We define an index of soil moisture when the temperature is above the threshold and an index of soil moisture when the temperature is below the threshold. In this model, the soil moisture is separated by a temperature threshold H^*.

$$y_{it} = \alpha D_{it}^{10-29} + \beta D_{it}^{29} + \left\{ \sum_m \delta_m \, M_{mit}\big|_{H<H^*} + \delta_m' \, M_{mit}\big|_{H>H^*} \right\} + \lambda_s t + \lambda_s' t^2 + c_i + \varepsilon_{it} \tag{s9}$$

where i is the county index, t is the time index, m is an index of soil moisture condition, s is an index for states, y shows average corn yields, D represents growing degree day variables, M shows conditional seasonal mean soil moisture, T stands for the time trend variable, H is the average daily temperature, H^* is the temperature threshold, and c_i is a time-invariant county fixed effect. Here, we define δ and δ' to test whether the marginal impact of soil moisture depends on heat.

S.4. Decomposition method

To show the significance of weather variation for crop yields, we estimate the historical impacts of heat and water. In a general form, we can decompose the impacts by taking the total derivative from the yield function. The general form is:

$$dy = \underbrace{\frac{\partial y}{\partial h} dh}_{\text{heat impacts}} + \underbrace{\frac{\partial y}{\partial m} dm}_{\text{water impacts}} \tag{s10}$$

where dy shows the deviation of crop yields from the trend, dh is the deviation of heat from the historical mean; and dm is the deviation of soil moisture from normal levels. We apply this to Model (2-a) while the trend is estimated assuming no variation in heat and water availability. We predict the overall variation in yields using the estimated coefficients of Model (2-a):

$$d\hat{y} = \frac{\partial y}{\partial D^{10-29}} dD^{10-29} + \sum_{m} \frac{\partial y}{\partial D_{m}^{29}} dD_{m}^{29} + \frac{\partial y}{\partial M} dM + \frac{\partial y}{\partial M^{2}} dM^{2} \tag{s11}$$

where d shows the differential, $d\hat{y}$ is the predicted variation of crop yields, and partial derivatives are the estimated coefficients. Then, we re-predict the yields using the estimated coefficients of Model (2-a) for normal soil moisture. Thus, the predicted variation in crop yields is driven only by the variation in observed heat.

$$d\hat{y}^{heat} = \frac{\partial y}{\partial D^{10-29}} dD^{10-29} + \frac{\partial y}{\partial D_{nl}^{29}} dD^{29} \tag{s12}$$

Finally, the difference between (s12) and (s13) shows the predicted impact of variation in water.

$$d\hat{y}^{water} = d\hat{y} - d\hat{y}^{heat} \tag{s13}$$

Note that the deviations are calculated for each year.

S.5. Correlation of mean seasonal soil moisture and other variables

The soil moisture output from WBM is informed mainly by soil moisture memory, heat, precipitation, and many other time-variant and time-invariant information. In a statistical study, a natural first step is to look at the correlation between these variables. To show that mean soil moisture is a different metric than mean precipitation, we have plotted the annual mean soil moisture versus annual cumulative precipitation in Fig. S2. This figure is a scatter plot for US counties for the growing season from 1981 to 2015. The simple correlation coefficient between them is 0.44. This rejects the hypothesis that soil moisture is highly correlated with precipitation. As mean precipitation has a linear relationship with cumulative precipitation, it shows that mean soil moisture is a different metric than cumulative or mean precipitation.

We have taken two other variables from WBM including soil moisture fraction and evapotranspiration (ET). Also, we have interpolated WBM soil moisture using an alternative method (nearest neighbor method). Here, we plot these variables against the volumetric soil moisture content to illustrate the correlation and differences. As shown in Fig. S3 two interpolations of soil moisture are closely correlated by R= 0.9997. Figures S4 and S5 are the scatter plots of seasonal ET and seasonal mean soil moisture fraction against volumetric soil moisture. The figures show the seasonal variables are not following a simple linear relationship. Figure S6 shows the scatter plot of cumulative growing degree days above 10˚C versus mean soil moisture for US counties for the growing season from 1981 to 2015. This indicates the soil moisture output is not a simple linear transformation of heat data.

S.6. Are the results different with alternative water metrics?

We re-estimate Model (1) with other related metrics of water availability to crops including simulated daily evapotranspiration of rainfed corn (ET) from WBM; daily soil moisture fraction (SMF) from WBM; and soil moisture content from different spatial interpolation of WBM grid cells to PRISM (nearest neighbor method versus original bilinear method).

The soil moisture fraction index considers the volumetric soil moisture content divided by field capacity. We have also considered the within-season standard deviation of ET and SMF. Note that we keep the degree days above 29˚C as an indicator of heat stress and the degree days from 10˚C to 29˚C as an indicator of beneficial heat to corn.

Table S1. reports regression results for these models. Columns 1 and 2 show a significant relationship with the mean of soil moisture fraction, its square term, and its within season standard deviation. Columns 3 and 4 with mean ET and within-season SD of ET also show a significant relationship. Column 5 shows that the other interpolation of soil moisture has a very close marginal coefficient and standard error compared to our original Model (1). The important finding is the marginal relationship for beneficial and harmful heat remains significant and not significantly different from Model (1). Overall, the main findings of the paper remain robust to the choice of alternative seasonal metrics of water availability.

S.7. Are the estimates different when considering the stages of plant growth?

How critical is separating the stages of plant growth in the yield function? We re-estimate the Model (1-b) considering bi-monthly metrics of seasonal soil moisture. Table S3. provides the estimation coefficients, standard errors, AIC, BIC, and R-squares statistics for Model (1-b) for Eastern, Western, and the continental US with bi-monthly mean soil moisture. The results suggest that the coefficients on extreme heat (dday 29˚C) are not significantly different from the model with seasonal mean soil moisture.

The results suggest that the marginal impact of mean soil moisture is higher in June-July. This is in line with agronomic literature as it suggests the water stress during pollination and the silking stage is more damaging. These stages are the most critical stage of development for corn. Water stress during this stage can cause higher yield loss than almost any other stage in the crop's development.

The marginal impact of mean soil moisture is not significant in August-September. This suggests that additional soil moisture can have a positive or negative impact on yield. This also makes sense as a high level of moisture can hurt the maturity and drying stage. High soil moisture at the end of the growing season can cause delayed grain maturity and may lead to delay in the harvest.

In Addition, the marginal impact of mean soil moisture in April-May is negative for the whole US and the Western US and significant at 90% confidence interval. This can be a result of the negative impacts of excess soil moisture on germination and early crop developments as a result of flooding and waterlogging.

S.8. Do the main findings change if we alter the geographical scope of the study

In this section, we estimate the main models separately for Eastern and Western US. Those counties with centroids on the left of 100th meridian are considered West. The idea is that water stress is less severe in the Western US as it is mostly irrigated. Table S2. provides the main descriptive statistics to compare these regions. Overall, Western US experiences more excess heat by 82 versus 58 dday 29˚C in the East. On average, Eastern US receives 601 mm of cumulative precipitation while it is only 271 mm in the Western US. On the other hand, within-season SD of soil moisture is 39 mm in the East while it is 13 mm in the west. Looking at the number of days with high/low soil moisture, only 11 days in the West soil moisture is not at normal levels, while this is 59 days in the East.

Table S4. shows the estimated coefficients, standard errors, adjusted R-squared, AIC, and BIC statistics for four models for Eastern US. Model (1-a) includes cumulative precipitation. Model (1-b) includes mean soil moisture metrics. The third column, similar to

Model (1-d), considers soil moisture extremes. The results suggest that the coefficient on the extreme heat is not significantly different from the estimations for the whole US.

Table S5. shows the estimated coefficients, standard errors, adjusted R-squared, AIC, and BIC statistics for four models for the Western US. The results suggest that the coefficients on the extreme heat are significantly different from the estimations for the whole US and the Eastern US. For example, the coefficient on dday 29˚C is -0.0020 in Model (1-a) for the West, while it was estimated -0.0056 in Model (1-a) for the East. This is around 65% lower damage for a given degree day above 29˚C.

We also re-estimate Model (2) for Eastern and Western US. The results of Model (2-a) are presented in Table S6. Column 1 shows the results for the whole US while columns 2 and 3 contain the results for the Western US and Eastern US, respectively. According to column 2, the coefficient on dday 29˚C and the extreme deficit is -0.0074 in the Western US which is significantly different from all other estimations for the Western US. These results indicate that, even in the Western US, *the damage from heat stress can be up to four times higher when combined with water stress*. The coefficient on excess heat and the extreme surplus is not significant (note that this is a very rare condition in the West).

The results of Model (2-b) for Eastern, Western, and whole US are shown in Table S7. As in column (3) of Table S7, the coefficient on normal soil moisture conditional to hot weather is 0.00010. The coefficient on normal soil moisture conditional to moderate weather is 0.00002. This indicates that yield response to water is up to four times more in hot weather. The marginal impact on soil moisture deficit index is 0.00008 in hot weather and is 0.00002 in moderate weather. This also supports the finding that the yield response to water is up to four times more in hot weather. Also, the results suggest that the damage from excess water is up to two times bigger in hot weather.

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Table S1. Estimating corn yields using ET and SMF from WBM

	Log CornYield	Log CornYield	Log CornYield	Log CornYield	Log CornYield
Degree days from 10˚C to 29˚C	.0003422***	.0003445***	.0003193***	.0003372***	.0003426***
	(.0000752)	(.0000741)	(.0000801)	(.0000751)	(.0000801)
Degree days above 29˚C	-.005298***	-.005343***	-.005017***	-.004884***	-.005115***
	(.00069)	(.0006681)	(.00064)	(.0006367)	(.0006914)
Mean daily soil moisture fraction	.2533803**	.9821037***			
	(.1107891)	(.2394119)			
Sqr. mean soil moisture fraction	-.1030471	-.777505***			
	(.1166278)	(.2402404)			
SD daily soil moisture fraction		-.509464***			
		(.1156073)			
Mean daily ET[1] (mm)			.4901121***	.6357687***	
			(.0735423)	(.0985801)	
Sqr. mean daily ET[1]			-.086206***	-.118748***	
			(.0234848)	(.0254433)	
SD daily ET[1]				-.2516986**	
				(.0997848)	
Mean moisture content (mm)[2]					.0036395***
					(.0006759)
Sqr. mean daily moisture content[2]					-.000017***
					(3.000e-06)
Observations	69923	69923	69923	69923	69923
R-squared	.4667911	.4712361	.4755177	.4770727	.4713225
Akaike's Crit	-21005.7	-21589.0	-22159.5	-22365.1	-21602.5
Bayesian Crit	-20969.0	-21543.3	-22122.9	-22319.4	-21565.9

Standard errors in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Notes: 1- ET shows the average daily evapotranspiration. 2- It shows the volumetric soil moisture interpolated from WBM to PRISM grid cells using the nearest neighbor method. Table lists regression coefficients and shows standard errors in brackets.

Table S2. Descriptive statistics of main variables for Eastern and Western US

Variables	East		West	
	Mean	Std. Dev.	Mean	Std. Dev.
Degree days from 10˚C to 29˚C	1877.79	433.54	1612.74	363.57
Degree days above 29˚C	58.01	57.13	82.11	80.29
Cumulative precipitation Apr-Sep (mm)	601.13	153.31	271.69	132.12
Mean daily soil moisture content (mm)	50.49	39.49	15.15	13.17
Number of days with high soil moisture	28.89	30.38	8.69	11.57
Number of days with low soil moisture	30.39	35.46	2.97	7.1
Surplus (sum of positive daily deviation, mm)	2546.95	2177.62	964.98	938.69
Deficit (sum of negative daily deviation, mm)	-2563.43	2200.22	-962.27	699.6
Degree days from 10˚C to 29˚C & low soil moisture	442.94	433.88	29.08	94.27
Degree days from 10˚C to 29˚C & high soil moisture	364	351.68	62.88	90.52
Degree days from 10˚C to 29˚C & normal soil moisture	1067.65	573.28	1462.24	426.27
Degree days above 29˚C & low soil moisture	20.19	32.55	.85	3.22
Degree days above 29˚C & high soil moisture	5.17	9.34	.76	2.41
Degree days above 29˚C & normal soil moisture	32.24	41.87	72.91	72.8
Index of extreme deficit	-1823.19	2339.6	-160.91	597.29
Index of extreme surplus	1942.11	2207.68	482.25	770.15
Index of normal soil moisture	-194.99	516.76	-406.16	434.96
Mean daily evapotranspiration (mm)	.6	.59	.15	.19
Mean daily soil moisture fraction	.71	.18	.68	.2
Mean daily soil moisture content (mm), alternative	50.52	39.41	15.17	13.2
Mean daily soil moisture content (mm), Apr-May	21.82	16.5	6.29	6.75
Mean daily soil moisture content (mm), Jun-Jul	17.7	15.77	5.14	4.53
Mean daily soil moisture content (mm), Aug-Sep	10.98	10.74	3.72	3.27
Observations	62094	62094	7829	7829

Table S3. Corn yield estimation with bi-monthly soil moisture metrics

	US Log CornYield	West Log CornYield	East Log CornYield
Degree days from 10˚C to 29˚C	.0003176***	.0004543***	.0002921***
	(.0000774)	(.0000853)	(.0000838)
Degree days above 29˚C	-.0044571***	-.0023373***	-.0047849***
	(.0006231)	(.0004904)	(.0006742)
Mean daily soil moisture content (mm), Apr-May	-.0029599*	.0045436**	-.0034124**
	(.0015561)	(.002061)	(.0015243)
Square of mean daily soil moisture content (mm), Apr-May	-9.800e-06	-.0000564	-2.600e-06
	(.000022)	(.0000581)	(.0000216)
Mean daily soil moisture content (mm), Jun-Jul	.0141021***	.0148123*	.013605***
	(.0019928)	(.0071408)	(.0020404)
Square of mean daily soil moisture content (mm), Jun-Jul	-.0001589***	-.0005616**	-.0001562***
	(.0000252)	(.0002422)	(.0000258)
Mean daily soil moisture content (mm), Aug-Sep	.0030501*	.007007	.0026044
	(.001805)	(.0049266)	(.0018059)
Square of mean daily soil moisture content (mm), Aug-Sep	-.0000385	-.000213	-.0000351
	(.0000291)	(.0002114)	(.0000294)
Observations	69923	7829	62094
R-squared	.4884616	.2782172	.515591
Akaike's Crit	-23898.8	-3040.6	-22112.9
Bayesian Crit	-23825.6	-2984.8	-22040.6

Standard errors are in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Notes: Table lists regression coefficients and shows standard errors in brackets.

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Table S4. Estimation of Model (1) for the East

	(1-a) Log CornYield	(1-b) Log CornYield	(1-d') Log CornYield
Degree days from 10˚C to 29˚C	.0003108***	.0003152***	.0003072***
	(.0000936)	(.0000868)	(.0000724)
Degree days above 29˚C	-.0056293***	-.0054707***	-.0052882***
	(.0007259)	(.0007343)	(.0006442)
Cumulative precipitation Apr-Sep (mm)	.0009245***		
	(.0002502)		
Square of cumulative precipitation Apr-Sep	-7.000e-07***		
	(2.000e-07)		
Mean daily soil moisture content (mm)		.00319***	
		(.0006763)	
Square of mean daily soil moisture content		-.0000158***	
		(3.000e-06)	
Index of extreme deficit			.0000379***
			(5.700e-06)
Index of extreme surplus			-.0000381***
			(2.700e-06)
Index of normal soil moisture			.0000292**
			(.0000112)
Observations	62094	62094	62094
R-squared	.4997799	.4989592	.5205428
Akaike's Crit	-20126.6	-20024.8	-22756.9
Bayesian Crit	-20090.4	-19988.6	-22711.8

Standard errors in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Notes: Table lists regression coefficients and shows standard errors in brackets. Model (1-d') is slightly different from Model (1-d) considering extreme deficit and extreme surplus metrics.

Table S5. Estimation of the Model (1) for the West

	(1-a) Log CornYield	(1-b) Log CornYield	(1-d’) Log CornYield
Degree days from 10˚C to 29˚C	.0004426*** (.0000829)	.0004484*** (.0000823)	.0004539*** (.0000862)
Degree days above 29˚C	-.0020381*** (.000423)	-.0023744*** (.0004911)	-.0022938*** (.0004752)
Cumulative precipitation Apr-Sep (mm)	.0005768 (.0003372)		
Square of cumulative precipitation Apr-Sep	-3.000e-07 (5.000e-07)		
Mean daily soil moisture content (mm)		.0078908** (.0027432)	
Square of mean daily soil moisture content		-.0000848** (.0000326)	
Index of extreme deficit			.0000255 (.0000271)
Index of extreme surplus			-9.800e-06 (7.600e-06)
Index of normal soil moisture			.0000762** (.0000309)
Observations	7829	7829	7829
R-squared	.2784229	.2768284	.2772401
Akaike's Crit	-3050.8	-3033.5	-3035.9
Bayesian Crit	-3022.9	-3005.6	-3001.1

Standard errors are in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Notes: Table lists regression coefficients and shows standard errors in brackets. Model (1-d’) is slightly different from Model (1-d) considering extreme deficit and extreme surplus metrics.

Table S6. West versus East in corn yield estimation with the interaction of heat and soil moisture (Model 2-a)

	(US) log CornYield	(West) log CornYield	(East) log CornYield
Degree days from 10˚C to 29˚C	.0003083*** (.0000685)	.0004344*** (.0000847)	.0002963*** (.0000736)
dday29˚C & SM 75+ mm below normal (extreme deficit)	-.0082398*** (.0014372)	-.0074467* (.0035727)	-.0082928*** (.0014365)
dday29˚C & SM 25-75 mm below normal (deficit)	-.0062069*** (.0009793)	-.0033152* (.001627)	-.0061966*** (.0009797)
dday29˚C & SM 0-25 mm around normal (normal)	-.0037559*** (.0004045)	-.0024412*** (.0005053)	-.0041335*** (.0004376)
dday29˚C & SM 25-75 mm above normal (surplus)	-.0055709*** (.0012041)	-.004754* (.0024763)	-.005625*** (.0011677)
dday29˚C & SM 75+ mm above normal (extreme surplus)	-.0140295*** (.0019083)	.0095881 (.0128016)	-.0143573*** (.0018101)
Mean daily soil moisture content (mm)	.0026635*** (.0008153)	.0080027** (.0028858)	.0025636*** (.0008324)
Square of mean daily soil moisture content	-.0000161*** (2.600e-06)	-.0000844** (.0000326)	-.0000156*** (2.600e-06)
Observations	69923	7829	62094
R-squared	.4921263	.2777862	.5149811
Akaike's Crit	-24401.6	-3035.9	-22034.8
Bayesian Crit	-24328.3	-2980.2	-21962.5

Standard errors in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Notes: Table lists regression coefficients and shows standard errors in brackets.

Table S7. West versus East in estimation of corn yields while splitting the soil moisture indicators (Model 2-b)

	(US) log CornYield	(West) log CornYield	(East) log CornYield
Degree days from 10˚C to 29˚C	.0003154***	.0004451***	.0002983***
	(.0000689)	(.0000919)	(.000074)
Degree days above 29˚C	-.004044***	-.0020707***	-.0044516***
	(.0005384)	(.0005793)	(.0005981)
Index of normal soil moisture when T > T*	.0001199***	.0001805	.0001034***
	(.0000342)	(.0001426)	(.0000358)
Index of extreme moisture surplus when T > T*	-.0000628***	-.0001173	-.0000586***
	(.0000151)	(.0001071)	(.0000149)
Index of extreme moisture deficit when T > T*	.000092***	-.0000526	.0000817***
	(.0000234)	(.0000978)	(.0000229)
Index of extreme moisture deficit when T < T*	.0000209***	.0000287	.0000223***
	(7.100e-06)	(.0000337)	(7.000e-06)
Index of extreme moisture surplus when T < T*	-.0000326***	-5.700e-06	-.0000334***
	(3.200e-06)	(6.500e-06)	(3.200e-06)
Index of normal soil moisture when T < T*	.000028**	.000063**	.0000247**
	(.0000105)	(.0000249)	(.0000102)
Observations	69923	7829	62094
R-squared	.5006312	.2782242	.5262193
Akaike's Crit	-25582.4	-3040.6	-23490.5
Bayesian Crit	-25509.2	-2984.9	-23418.2

Standard errors in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Notes: Table lists regression coefficients and shows standard errors in brackets.

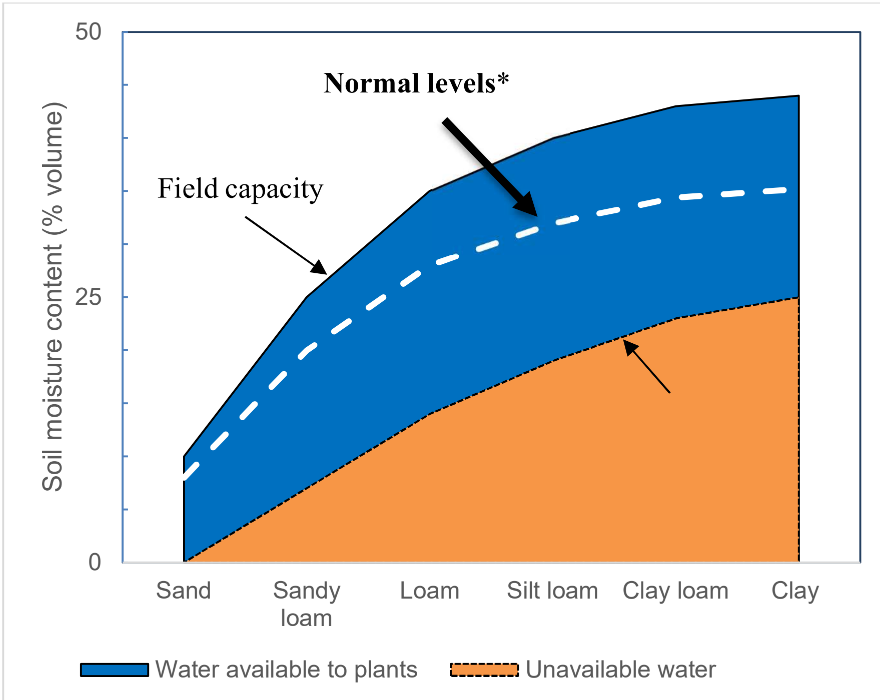

Figure S1. Soil texture affects normal moisture levels. The sandy soil has the lowest normal level while the clay has the highest normal levels.

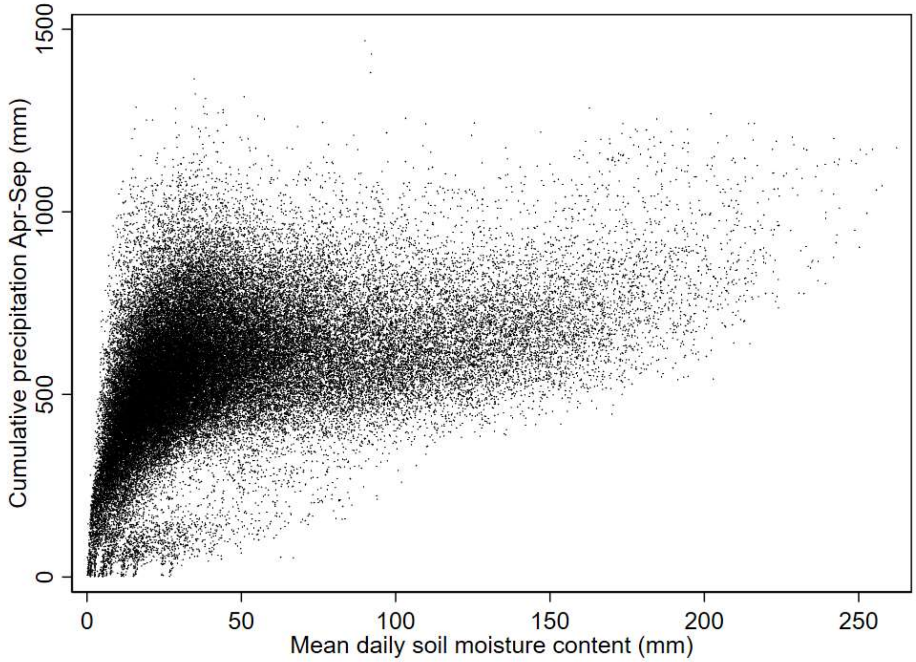

Figure S2. WBM mean soil moisture versus PRISM cumulative precipitation for 1981-2015 by US counties.

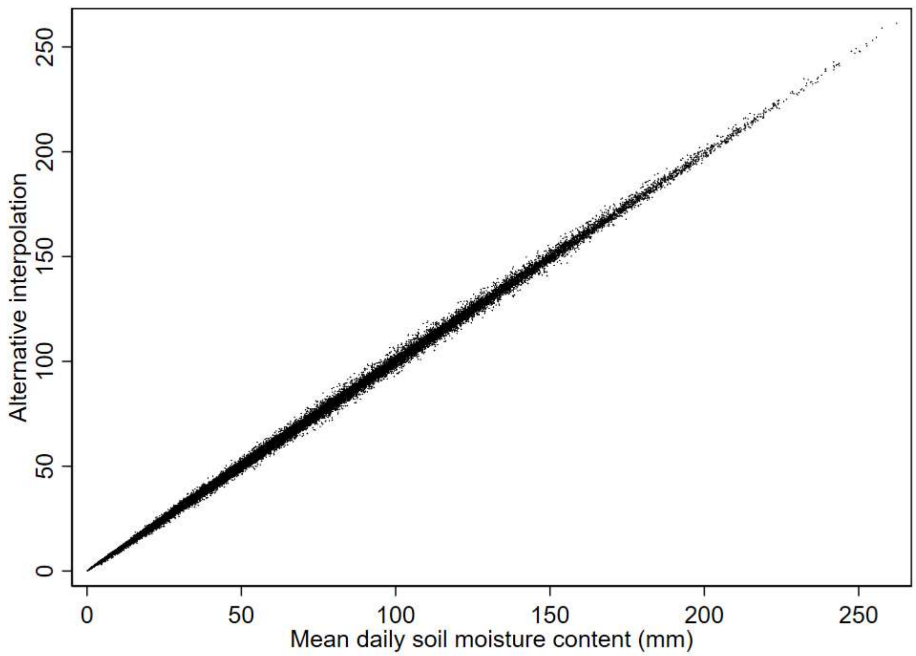

Figure S3. County-level mean seasonal soil moisture based on bilinear interpolation versus alternative interpolation (nearest-neighbor) from WBM 6 arcmin grids to PRISM 2.5 arcmin resolution for the 1981-2015 period.

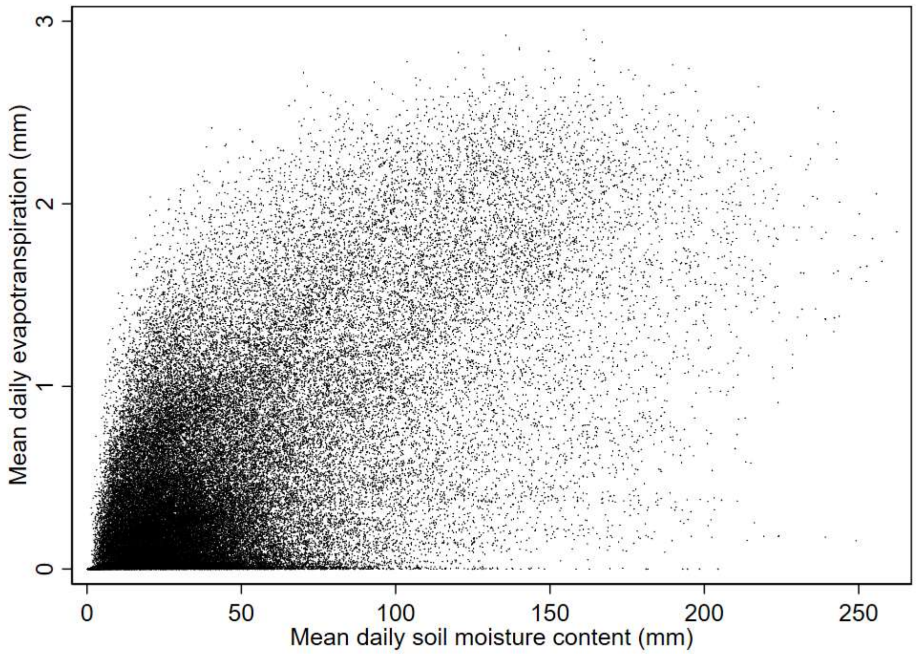

Figure S4. County-level mean soil moisture versus mean ET aggregated from WBM for the 1981-2015 period.

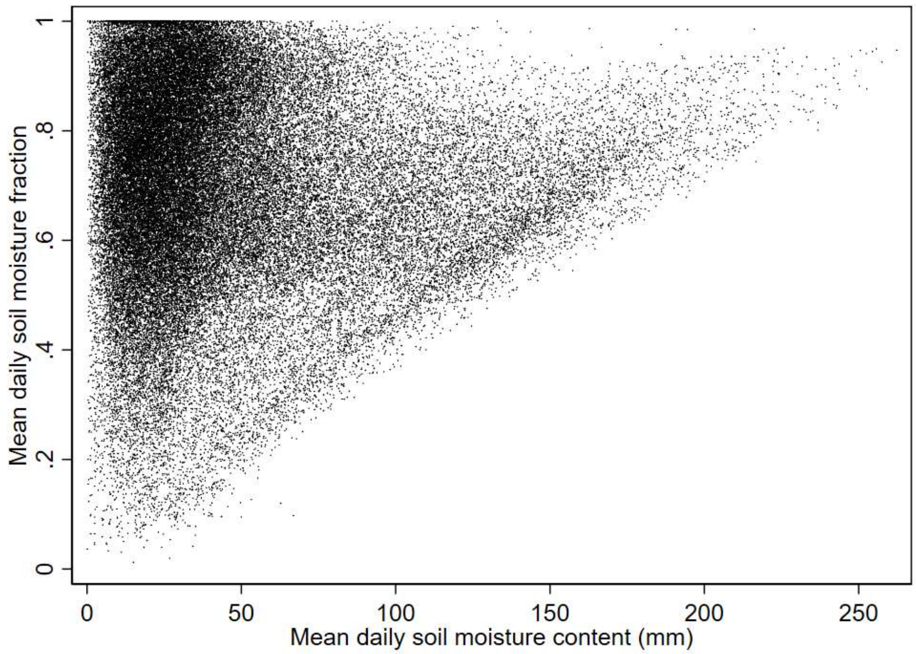

Figure S5. County-level mean volumetric soil moisture content versus mean of soil moisture fraction aggregated from WBM for the 1981-2015 period.

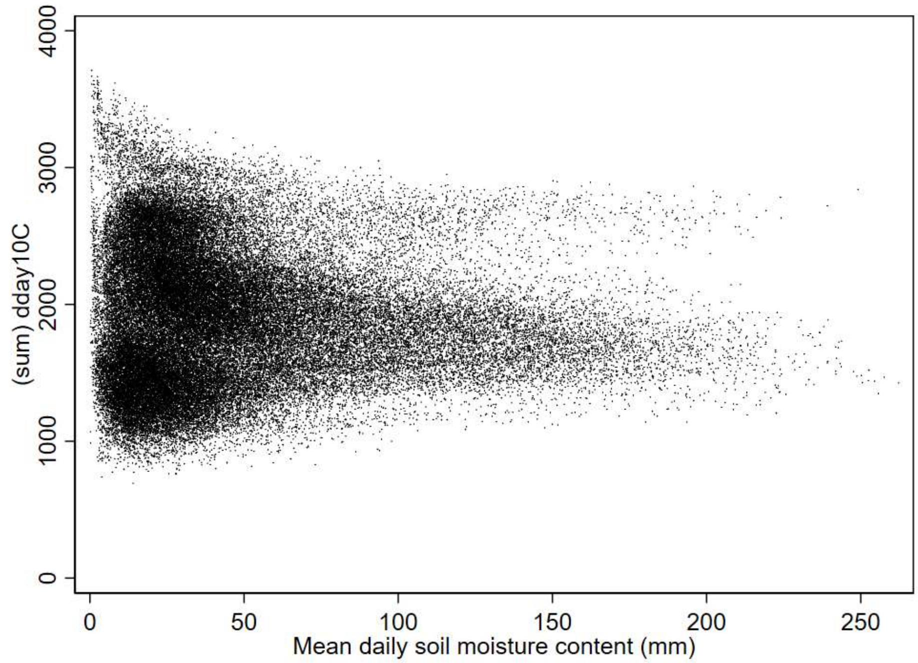

Figure S6. County-level seasonal mean soil moisture versus seasonal heat index aggregated from WBM and PRISM for the 1981-2015 period.