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Soil organic matter protects US maize yields and lowers crop insurance payouts under drought

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Abstract

Higher levels of soil organic matter improve soil water retention, meaning they could mitigate agricultural yield losses from drought. Yet evidence to support such claims is mixed and incomplete. Using data from 12 376 county-years in the United States of America, we show that counties with higher soil organic matter are associated with greater yields, lower yield losses, and lower rates of crop insurance payouts under drought. Under severe drought, an increase of 1% soil organic matter was associated with a yield increase of 2.2 ± 0.33 Mg ha^{-1} (32.7 bu ac^{-1}) and a 36 ± 4.76% reduction in the mean proportion of liabilities paid. Similar, yet smaller, effects were found for less severe levels of drought and this effect was reduced as soil clay content increased. Confirmatory pathway analyses indicate that this positive association of soil organic matter and yields under drought is partially explained by positive effects of soil organic matter on available water capacity and cation exchange capacity, but that soil organic matter may be imparting yield protection via mechanisms not fully captured by those metrics. Overall, our results suggest soil organic matter predicts yield resilience at regional scales in the United States. We argue that data on soil organic matter should be used in agricultural policy and financial planning, with our analyses providing quantitative evidence of the co-benefits of soil organic matter believed fundamental to advancing soil health and carbon sequestration initiatives.

1. Introduction

Rain-fed agriculture, which made up 75% of global cropland use as of 2000 (Portmann *et al* 2010), is highly susceptible to extreme weather conditions, such as heat and drought. Extreme heat accelerates plant development, effectively shortening growing season length and reducing harvest index, and in extreme instances, extreme heat causes plant reproductive failures, such as kernel abortion in maize, that drastically reduce yields (Sage and Kubien 2007, Craufurd and Wheeler 2009, Hsiao *et al* 2019). Similarly, drought leads to elevated vapor pressure deficit which can lead to increased transpiration by plants, closing of stomata, and ultimately reduced rates of photosynthesis that slow plant growth and reduce grain yields (Lobell *et al* 2013, 2014). Climate change is predicted to increase the incidence and severity of

droughts and floods (Meehl *et al* 2007, Luber and McGeehin 2008), thereby increasing the risk of crop failures and yield losses (Urban *et al* 2012). Conservative estimates for maize suggest yields could drop between 20% and 80% in the US under plausible future climate scenarios (Schlenker and Roberts 2009, Lobell *et al* 2014, Hsiao *et al* 2019). Such scenarios threaten global food security and suggest that resilience planning to mitigate these impacts is necessary.

Increasing soil organic matter can increase soil water holding capacity on similarly textured soils (Hudson 1994, Minasny and McBratney 2018) and improve water infiltration (Boyle *et al* 1989, Elliott and Efetha 1999, Franzluebbers 2002) by supporting greater aggregate formation and, hence, a greater volume of pore spaces (Lado *et al* 2004). Researchers have argued that soils with higher organic matter can retain more water under vapor pressure deficit,

protecting crops from losses induced by extreme heat and drought better than low organic matter soils (Bot and Benites 2005, Iizumi and Wagai 2019, Carminati and Javaux 2020). Yet recent work suggests the actual effect of soil organic matter on plant available water is modest (Libohova *et al* 2018, Minasny and McBratney 2018), and it is unclear whether these effects on water retention are great enough to reduce drought-induced yield losses. Studies have demonstrated that higher soil organic matter is associated with lower long-term interannual yield variability at regional scales (Pan *et al* 2009, Williams *et al* 2016). But lower variability is not necessarily indicative of greater resilience or protection against yield losses and/or crop failure under adverse conditions. Some field-level studies have shown that practices known to increase soil organic matter can protect yields (Gaudin *et al* 2015, Bowles *et al* 2020), but these do not explicitly test the relative effect of organic matter and do not provide information at county or regional scales which are arguably most relevant to policy initiatives. Furthermore, these studies did not attempt to quantify how the effect of soil organic matter on yields does or does not scale under different drought conditions.

In light of these evidence gaps, we quantified the impact of soil organic matter on agronomic risk to drought in the United States of America. We analyzed county-level maize (*Zea mays* L.) yield and crop insurance payouts in the US from 2000 to 2016 in combination with soil characterization data and county-level Standardized Precipitation Evapotranspiration Index (SPEI) data. Data were gathered for 754 counties where maize production was predominantly rain-fed, representing a total of 12 376 county-years, 5945 of which experienced drought conditions over the summer growing season (Kane *et al* 2020). We hypothesized that counties with higher levels of soil organic matter in surface soils (0–30 cm depth) where most of the fine-root biomass is found, would be less prone to yield losses in drought years given expected positive effects of soil organic matter on crop water availability and that, as a result, a lower proportion of crop insurance liabilities would be paid out in drought years.

2. Methods

2.1. Data collection
2.1.1. Maize yield data
We collected mean maize (*Zea mays* L.) yield (Mg ha^{-1}) data for all US counties between the years 2000 and 2016 for which maize yield data were available from the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) (USDA NASS Staff 2018) accessed via the *rnassqs* package (Potter *et al* 2019) in the R v.3.6.3 statistical software environment (R Core Team 2020). Data were limited to the years 2000–2016 to minimize the

confounding effect improvements in maize genetics may have on yield data and because other data used to estimate drought incidence in each county detailed below were only available beginning in the year 2000. We removed data from counties in which corn was not grown for at least 16 of the 17 years in the study period. Yield data were then detrended on a county basis per the method detailed in Lu *et al* (2017). Briefly, we fit a locally weighted regression model wherein yield was the dependent variable and year was the independent variable. Models were fit using the R package *caret* (Kuhn *et al* 2020) using a ten-fold cross validation approach wherein the span parameter was constrained to a range of 5–10 years and the degree parameter was allowed to be either 1 (linear) or 2 (polynomial). We then added the yearly residuals of these models to the long-term county average yield to estimate detrended yield for each county-year in the study period, and we also divided the observed yield by the predicted yield of these models for each county-year to estimate yield anomaly.

Because soil organic matter might protect yields by improving soil water dynamics, irrigation could mask the effects of soil organic matter on agricultural resilience. As such, we restricted the analysis to primarily non-irrigated acres. We also retrieved data from USDA NASS (USDA NASS Staff 2018) via the *rnassqs* (Potter *et al* 2019) on the total number of corn acres harvested in each county-year and the total number of irrigated corn acres harvested in each county-year for the US Agricultural Census years of 1997, 2002, 2007, and 2012. The US Agricultural Census is conducted every 5 years, so data on irrigation within our study period is only available for those years. We then calculated the percent of maize-growing acres that were irrigated in each county for each census year, averaged those figures across all four census years, and filtered yield data to those counties in which corn-growing acres were on average $\leqslant$5% irrigated during the study period and in which average acres irrigated had a standard deviation of $\leqslant$1% across the four census years for which data were retrieved.

2.1.2. Drought data
We retrieved county-level SPEI figures from the Center for Disease Control (National Environmental Public Health Tracking Network 2018). SPEI is a multi-scalar drought index based on the similar Standardized Precipitation Index (Vicente-Serrano *et al* 2009, 2012). Differences between cumulative monthly precipitation and potential evapotranspiration are calculated for a chosen time scale (i.e. 1 month, 3 months, etc). These figures are then standardized based on a log-logistic distribution so that they are comparable across locations. The CDC dataset we used is based on a 1 month standardization. We summarized SPEI data in each county-year by calculating the mean of monthly SPEI

values for the summer growing season months of May to August.

In addition to SPEI, we also retrieved drought data from The National Drought Mitigation Center (The National Drought Mitigation Center 2019c), which reports on a daily basis the percent area of each county that is at each level of their drought index: D0 (no drought)—D4 (severe drought). This drought index is a categorization based on the Palmer Drought Severity Index, Standardized Precipitation Index, soil and streamflow models, and local expert assessment/verification by USDA field agents (The National Drought Mitigation Center 2019b). We then converted these coverage statistics to a daily Drought Severity Classification Index (DSCI), per the instructions of the US Drought Monitor website (The National Drought Mitigation Center 2019a). Briefly, DSCI is a weighted sum of the percent area of each county under each drought index level. We then subset daily DSCI data to the months of May to August, the months that are most crucial to maize growth and yield, and averaged them for each county-year across the study period. DSCI data were not used in our primary analyses but were instead used in a set of sensitivity analyses (supplementary information) to determine the relative importance of how drought is quantified on estimating the mitigating effect of soil organic matter on yields under drought.

2.1.3. Crop insurance data
The USDA Risk Management Agency collates a variety of data on the US crop insurance market on an annual basis, including total liabilities, total indemnities, and cause of loss. These data are available at the county-level via the USDA Southwest Climate Hub's AgRisk Viewer (Southwest Climate Hub 2018). We retrieved data on total liabilities and total indemnities in USD for maize due to loss by drought for the same set of counties for which we retrieved yield data. We then used these data to calculate loss cost (Reyes and Elias 2019), a unitless index based on the ratio of total indemnities to total liabilities in a given county-year. Loss cost implicitly accounts for differences in USD figures across years due to inflation, as well as differences across counties due to differences in total output and coverage patterns.

2.1.4. Soil data
To aggregate soil data for each county in our analysis we first identified those areas in each county that are primarily used for maize production. To do so, we used the 'Corn Frequency' raster available at USDA NASS's CropScape portal, which reports how many years between 2008 and 2017 each pixel was used for maize production (Han *et al* 2014). We then subset this raster to only those pixels in which maize was produced for two or more years to identify pixels from any field in which maize was grown with relative consistency but not opportunistically (e.g. in a high

price year), while also eliminating non-crop areas. This subset of pixels was then used to generate a masking layer used in subsequent steps.

The gSSURGO database is spatially organized as a series of discrete polygons referred to as map units that are composed of different component soil series. Associated with each soil series is characterization data organized by pedological horizon, including soil texture, soil organic matter, and measures of soil biophysical characteristics. As such, we first used the *aqp* (Beaudette *et al* 2020) package in R to convert characterization data for each component soil series to a fixed depth increment of 0–30 cm to represent the typical rooting zone of maize. We then calculated a representative map unit value for each soil characteristic soil organic matter (%), clay content (%), H_3O^+ concentration (mol), cation exchange capacity (meq $100 \, g \, soil^{-1}$), and available water capacity (%) by calculating a map unit mean weighted by the relative proportions of each component soil series in a map unit. We then converted the data to a raster format and used the masking layer described previously to remove soil data in each county from areas where maize is not consistently grown. Finally, we used these masked rasters to calculate county-level means for all soil properties we then used in our analyses.

2.1.5. Cropping system management
For the purposes of this study we did not include data on the rates of different cropping system management strategies or practices, such as mean fertilizer rate by county or incidence of conservation tillage by county. Such data are not available at the county level or on a timestep that would make them sufficiently useful for our analysis. For example, data on per area fertilizer use is available via USDA NASS only at the state level, and questions on implementation of conservation agriculture practices were only recently included in the agricultural census. Given these inconsistencies in data, we could not account for management effects with a fixed effect for each practice. Instead, we accounted for them by implementing a random effect for state (section 2.2). We argue that since farms in the same state are generally more likely to implement fertilizer rates and management practices similar to other farms in their state than those out of their state, our model accounts to some degree for broad differences in management. Whereas direct estimation of the effect of different management practices would be preferable, sufficient data simply do not exist and use of current, sparser data could lead to flawed inference.

2.2. Data analysis
Initial data analysis demonstrated that the yield response to SPEI begins to saturate above SPEI values of 0, indicating that when the balance of precipitation and evapotranspiration is negative, yields drop below the typical yield potential of a given area. Additionally, we found that when SPEI decreased (i.e. drought

conditions became more severe) the impact of soil organic matter was greater on maize yield (Mg ha^{-1}), yield anomaly, and loss cost (supplementary information). As such, we chose to subset our data into different levels of drought severity based on SPEI and then analyze each subset to understand how the effect of soil organic matter on each outcome variable changed as drought severity changed. Drought severity thresholds were calculated based on the global mean and standard deviation of SPEI. Very severe drought was defined as greater than two standard deviations from the global mean (SPEI $\leqslant -1.02$); severe drought as between one and two standard deviations from the mean ($-1.02 <$ SPEI $\leqslant -0.46$); moderate drought as between one standard deviation from the mean and the mean ($-0.46 <$ SPEI $\leqslant 0.10$); and normal conditions as greater than or equal to the mean (SPEI > 0.10).

Within each of these drought subsets we then fit a series of models wherein the dependent variable in these models was either yield (Mg ha^{-1}), yield anomaly, or loss cost. Independent variables across all models included soil organic matter, soil clay content, and soil H$_3$O$^+$ concentration. These variables were chosen by fitting a multivariate linear model with multiple potential independent variables then assessing variance inflation factors to eliminate spurious, highly collinear variables. We also included a random effect of state to account for possible impacts of geographic differences in management and production environment on model outcomes not accounted for in the data we collected. For yield and yield anomaly, linear mixed effects models including all possible interaction effects were fit using a restricted maximum likelihood approach in the *lme4* (Bates *et al* 2020) package in R. For loss cost, a mixed effects Tobit regression model was fit using a Newton–Raphson maximization approach in the *censReg* (Henningsen 2020) package in R to account for the fact that loss cost was left censored at a value of 0. Prior to model fitting, all observations of each independent variable were standardized so that coefficient estimates would also be standardized. Data standardization was done by subtracting the mean of a given variable from each observation and then dividing that value by 2× the standard deviation of that variable (Gelman 2008).

Finally, we conducted a series of confirmatory path analyses to evaluate to what extent the impacts of soil organic matter on maize yields were mediated by their impacts on soil available water capacity and cation exchange capacity, a proxy variable for soil fertility, under both drought and normal conditions. First, we split data into those observations from normal SPEI years (SPEI > 0.10) and drought SPEI years (SPEI $\leqslant 0.10$), and then calculated the mean yield (Mg ha^{-1}) for each county under either set of conditions. We then employed a piecewise structural equation modeling approach using the *piecewiseSEM* (Lefcheck *et al* 2019) package in R to fit models in
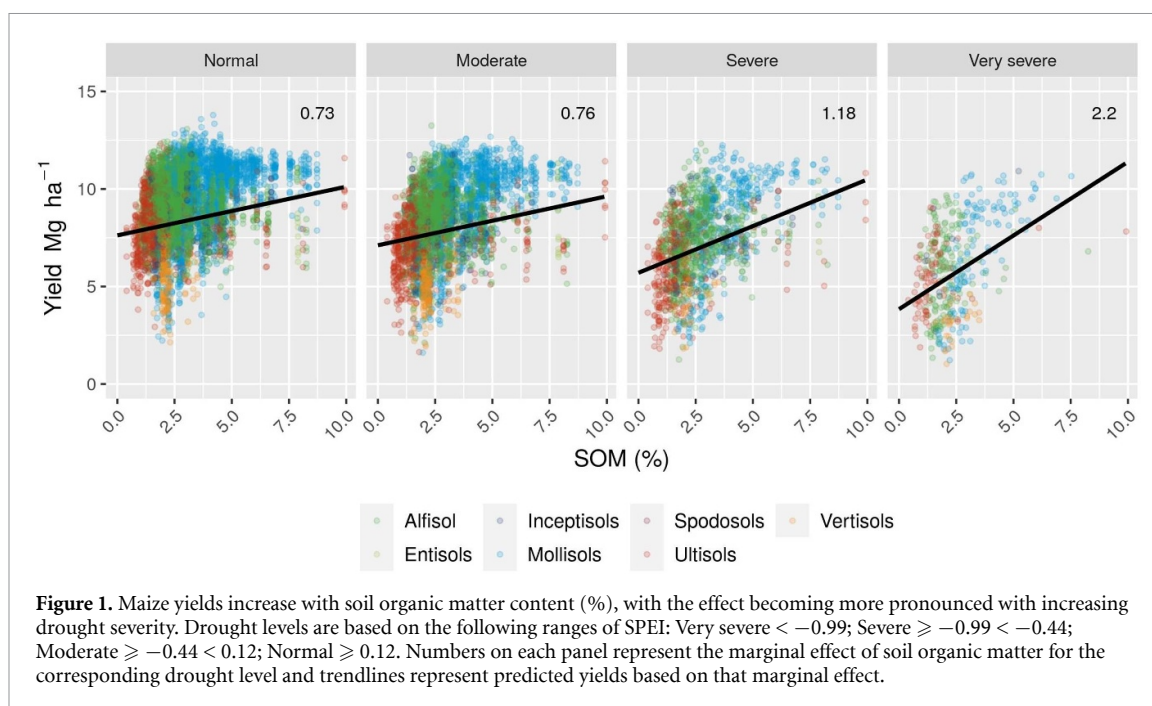
which the effects of soil organic matter were either partially mediated or fully mediated by its effects on available water capacity and cation exchange capacity. Briefly, the fully mediated SEM was such that available water capacity and cation exchange capacity were modeled as functions of soil organic matter and yield was modeled as a function of available water capacity and cation exchange capacity. Whereas, in the partially mediated SEM, available water capacity and cation exchange capacity were modeled the same way, but soil organic matter was included as an additional independent variable for modeling yield. To determine the most parsimonious model, we compared models via an analysis of variance and on the basis of AIC/BIC scores. Coefficients were extracted from the final model and standardized to then assess whether or not effects of organic matter on yields under drought were mediated by its impacts on available water capacity and cation exchange capacity. An initial analysis with all data in either SPEI category indicated a negative relationship between cation exchange capacity and yields. When we manually inspected data we found that this result was the consequence of outlying cation exchange capacity values, defined as being two standard deviations greater than the mean (CEC $\geqslant 31.9$), with extremely high clay content. As such, we removed these outliers for the final path analysis to better estimate effects on typical soils, but include results from a path analysis including these observations in supplementary information.

3. Results and discussion

3.1. Maize yields and yield anomalies

We found that across all county-years and possible weather conditions, soil organic matter content was a strong positive predictor of yield. Soil organic matter had a standardized marginal effect of 0.83 with a standard error of 0.04, meaning an increase of 1% soil organic matter was associated with an increase in yields of 0.83 ± 0.04 Mg ha^{-1}. This observed relationship between soil organic matter and yield is consistent with other studies which show yield increases are associated with higher levels of soil organic matter (Oldfield *et al* 2019). Our analysis extends these observations by showing that as drought conditions became more severe, the marginal effect of soil organic matter on yields increased (figure 1; table 1). For example, under moderate drought conditions ($-0.46 \leqslant$ SPEI < 0.12) an increase of 1% soil organic matter was associated with an increase in yields of 0.76 ± 0.07 Mg ha^{-1}, and under very severe drought conditions (SPEI < -1.02) a 2.2 ± 0.33 Mg ha^{-1} increase. Interaction effects of other soil properties with soil organic matter also emerged across the severe, moderate, and normal drought categories (table 1). Sensitivity analyses of these interaction effects revealed that in many

Figure 1. Maize yields increase with soil organic matter content (%), with the effect becoming more pronounced with increasing drought severity. Drought levels are based on the following ranges of SPEI: Very severe < -0.99; Severe $\geqslant -0.99 < -0.44$; Moderate $\geqslant -0.44 < 0.12$; Normal $\geqslant 0.12$. Numbers on each panel represent the marginal effect of soil organic matter for the corresponding drought level and trendlines represent predicted yields based on that marginal effect.

Table 1. Results of linear mixed effects models across multiple levels of drought severity relating yield (Mg ha^{-1}) to soil organic matter (SOM, %), clay (%), and H$_3$O$^+$ concentration (mol). Coefficients for terms are standardized. Sample numbers for each drought level are as follows: Very severe, $n = 410$; Severe, $n = 1537$; Moderate, $n = 3998$; Normal, $n = 6431$. Conditional coefficient of determination for each model is as follows: Very severe, $R^2 = 0.53$; Severe, $R^2 = 0.45$; Moderate, $R^2 = 0.51$; Normal, $R^2 = 0.59$.

Drought	Term	Coefficient	Std. error	p
	SOM	2.1976	0.3339	< 0.0001
	Clay	0.4999	0.3355	0.1371
	H$_3$O$^+$	0.5665	0.6013	0.3467
Very severe	SOM:Clay	0.6549	0.6312	0.3001
	SOM:H$_3$O$^+$	0.0426	0.9302	0.9635
	Clay:H$_3$O$^+$	1.0140	0.9089	0.2653
	SOM:Clay:H$_3$O$^+$	0.9120	1.6866	0.5890
	SOM	1.1820	0.1270	< 0.0001
	Clay	-0.1776	0.1340	0.1852
	H$_3$O$^+$	-0.3637	0.1716	0.0342
Severe	SOM:Clay	0.8457	0.2340	0.0003
	SOM:H$_3$O$^+$	-0.5317	0.2429	0.0288
	Clay:H$_3$O$^+$	-0.0274	0.2900	0.9249
	SOM:Clay:H$_3$O$^+$	-1.6099	0.5223	0.0021
	SOM	0.7616	0.0687	< 0.0001
	Clay	0.3132	0.0718	< 0.0001
	H$_3$O$^+$	-0.3794	0.0949	0.0001
Moderate	SOM:Clay	0.6793	0.1189	< 0.0001
	SOM:H$_3$O$^+$	-0.2837	0.1264	0.0249
	Clay:H$_3$O$^+$	-0.2869	0.1549	0.0640
	SOM:Clay:H$_3$O$^+$	-0.5372	0.2941	0.0678
	SOM	0.7266	0.0514	< 0.0001
	Clay	0.2085	0.0577	0.0003
	H$_3$O$^+$	-0.5189	0.0856	< 0.0001
Normal	SOM:Clay	0.5992	0.0985	< 0.0001
	SOM:H$_3$O$^+$	-0.1456	0.1219	0.2322
	Clay:H$_3$O$^+$	-0.2103	0.1445	0.1456
	SOM:Clay:H$_3$O$^+$	0.1430	0.2600	0.5822

cases outlying observations were responsible for the interaction. When those outliers were removed, the size and significance of interaction effects and corresponding main effects were diminished (supplementary information (available online at stacks.iop.org/ERL/16/044018/mmedia)). However, interaction effects of soil organic matter and clay content were robust to outlier observations and
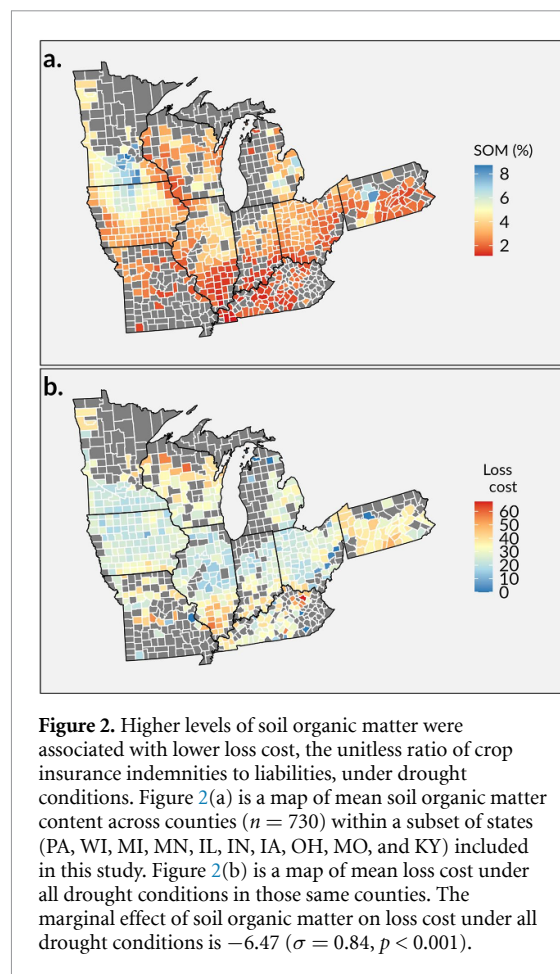
indicated that the effect of soil organic matter on yields remained positive at higher levels of clay but was diminished relative to lower clay soils. This result is consistent with broad-scale studies which demonstrate the primary importance of clay on the water holding capacity of soils and the diminished impact of organic matter when clay is high (Libohova *et al* 2018, Minasny and McBratney 2018). Nonetheless, our results show the effect of soil organic matter is still positive, regardless of clay content, and improves maize yields, and that soil organic matter was the only soil property that consistently buffered yields against drought conditions.

To more fully evaluate whether this greater relative yield advantage under drought is because soil organic matter protects against drought-induced yield losses, we also evaluated the relationship between soil organic matter and annual yield anomaly, the ratio of observed yield to expected yield estimated from long-term trends (Lu *et al* 2017). Under very severe drought conditions (SPEI < -1.01) an increase of 1% soil organic matter content was associated with a mitigation of yield losses of $12 \pm 0.03\%$, under severe drought conditions ($-1.01 \leqslant$ SPEI < -0.46) this effect decreased to a $5 \pm 0.01\%$ mitigation, and under moderate drought ($-0.46 \leqslant$ SPEI < 0.10) the effect was non-significant (table S2).

Further examination of yield anomaly data revealed that counties with lower soil organic matter content have high interannual variability, outperforming historical yield trends in favorable conditions but experiencing greater losses relative to historical trends under adverse conditions. Whereas counties with high soil organic matter have low interannual variability and consistently yield near expected yields based on historical trends, even under adverse drought conditions. For example, in counties with greater than 2.5% soil organic matter content, the mean of soil organic matter content across all counties in this study, the interquartile range for yield anomalies was 98%–107% of expected yield under normal conditions and 91%–104% under all drought conditions. By contrast, counties with lower than 2.5% soil organic matter ranged from 99% to 114% of expected yield under normal conditions and 82%–104% under all drought conditions. This pattern is consistent with previous studies demonstrating that higher soil carbon is associated with lower long-term interannual yield variability (Pan *et al* 2009, Williams *et al* 2016). Our findings offer additional insight by demonstrating that those reductions in interannual variability are partly explained by the association of higher soil organic matter and lower yield losses under drought conditions.

3.2. Crop insurance
Given the decrease in yield risk associated with greater levels of soil organic matter, we expected that

Figure 2. Higher levels of soil organic matter were associated with lower loss cost, the unitless ratio of crop insurance indemnities to liabilities, under drought conditions. Figure 2(a) is a map of mean soil organic matter content across counties ($n = 730$) within a subset of states (PA, WI, MI, MN, IL, IN, IA, OH, MO, and KY) included in this study. Figure 2(b) is a map of mean loss cost under all drought conditions in those same counties. The marginal effect of soil organic matter on loss cost under all drought conditions is -6.47 ($\sigma = 0.84$, $p < 0.001$).

lower yield risk would be reflected in crop insurance payouts to farmers. Specifically, we expected that counties with higher soil organic matter would have lower loss cost (Reyes and Elias 2019), a metric based on the ratio of total indemnities to total liabilities. Our results support this expectation, showing that soil organic matter is associated with reduced loss cost under drought conditions and that the marginal effect of soil organic matter increases as drought severity increases (figure 2). Under very severe drought conditions (SPEI $\leqslant -1.02$), an increase in soil organic matter of 1% was associated with a $36 \pm 4.76\%$ reduction in loss cost (table S3). Similar to yield anomaly, though, this effect decreases sharply as SPEI approaches normal. Soil organic matter was associated with an $8.4 \pm 1.41\%$ reduction in loss cost under severe drought conditions ($-1.02 <$ SPEI $\leqslant -0.46$) and just a $4 \pm 0.73\%$ reduction under moderate drought ($-0.46 <$ SPEI $\leqslant 0.10$). Nevertheless, given the expectation of increasing frequency of severe droughts (Adams *et al* 1990, Meehl *et al* 2007, Hayhoe *et al* 2010), our results suggest that it would be strategic for rain-fed US agriculture to directly incorporate differences in soil properties into policy and insurance planning for yield resilience.

3.3. Path analyses
The fact that we found that soil organic matter appeared to impart such effective protection against
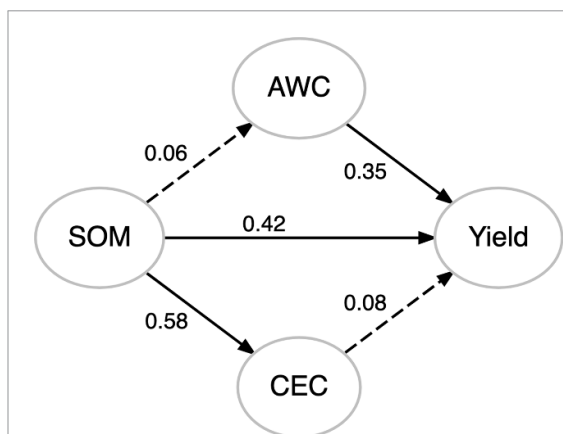
Figure 3. Increases in yield under drought associated with increasing soil organic matter appear only partially mediated by increases to soil available water capacity induced by higher soil organic matter. Figure 3 is a diagram of a structural equation model of best fit developed during a series of confirmatory pathway analyses. Numbers on each arrow represent standardized coefficients of the relationship between the variables connected, and the direction of arrows indicate variable dependence. Solid lines indicate statistically significant ($p \leqslant 0.05$) relationships and dotted lines indicate non-significant relationships.

yield losses under severe drought appears inconsistent with results from recent studies using large soil databases into how soil organic matter influences the plant available water capacity in soils. Briefly, the ability of soils to provide water to plants is often estimated as 'available water capacity', which typically is the difference in water content of saturated soil samples dried on pressure plates at -1500 kPa and -33 kPa (Soil Survey Staff 2015, Cassel and Nielsen 2018). These analyses have suggested that the net impact of soil organic matter on available water capacity is relatively modest and contingent on soil texture (Libohova *et al* 2018, Minasny and McBratney 2018). To investigate potential discrepancies in conclusions between these past studies and our work, we performed a series of confirmatory path analyses (Shipley 2009, Lefcheck 2019) to investigate the extent to which soil organic matter associations with yields under drought and non-drought conditions are related to its influence on available water capacity and cation exchange capacity, used here as a proxy measure of soil fertility. We found that soil organic matter was strongly associated with cation exchange capacity but only weakly associated with available water capacity, and under both drought and non-drought conditions, cation exchange capacity and available water capacity were positively associated with yields (figure 3). However, our confirmatory path analysis also suggested that soil organic matter had an independent, unmediated positive effect on yields under both drought and non-drought conditions (table S4).

These results confirm that soil organic matter has a positive influence on yields via its effects on available water capacity and soil fertility. But it also suggests that soil organic matter likely influences plant water

availability and soil fertility in ways not captured by how those properties are commonly measured. Although our analyses cannot resolve these additional influences, we do know that soil organic matter affects other important soil biophysical properties, such as porosity, bulk density, and water infiltration (Boyle *et al* 1989, Franzluebbers 2002, Lado *et al* 2004, Libohova *et al* 2018). Favorable changes in all of these properties may increase the soil volume from which plants can draw water and may effectively increase the supply of water to plants between rain events. In addition, soil organic matter is also an important source of key nutrients for plant growth. Under drought conditions, water transpiration and radiation efficiency in maize plants increase with increasing nitrogen fertilizer use (Teixeira *et al* 2014) and nitrogen fertilizer can be important for maintaining key metabolic functions and increasing yield (Zhang *et al* 2007). Further work is required to ascertain whether soil organic matter has similar, nutrient-mediated effects under drought conditions.

3.4. Broader implications
Our analyses are based on subcontinental-scale variation in soil organic matter and yield outcomes. As such, they cannot be used to argue directly that field-scale increases in soil organic matter achieved through conservation agricultural practices such as cover-cropping or reduced tillage, will lead to the same level of meaningful yield protection under drought. More specifically, the demonstrated increases in soil organic matter such practices often achieve is smaller than the relative range of soil organic matter content represented in this study, and the magnitude of the effect of a soil organic matter demonstrated here may not be maintained at the field scale. Similarly, our results are specific to the 'corn belt' region of the US and we only examined the impact of soil organic matter under drought on maize. Much of this region comprises relatively high organic matter soils, and maize is a drought sensitive crop. Last, our results likely mask substantial variation in management practices (i.e. fertilizer regimes, tillage, cover crops, etc) that could also impart resilience on rain-fed maize systems. Additional farm-scale evidence is required to understand whether increases in soil organic matter over time are associated with resilience to drought conditions at the farm scale, whether or not management practices can impart similar resilience, and whether or not these results are generalizable to other geographies, agro-ecological zones, and crops.

Nevertheless, our results do appear to have the potential to directly inform agricultural financing programs and policy in the US. At present, knowledge of risk is incorporated into US Federal Crop Insurance Programs (FCIP) only indirectly. Premiums are based on the Actual Production History (APH) of a given area and farm, and current policy dictates that

APH be calculated based on a 10 year trend excluding years in which yield losses were extreme (Bryant and O'Connor 2017). While differences in soil organic matter and other biophysical limitations to resilience are arguably endogenous to these yield data, APH may become less predictive of risk under future climate scenarios where drought frequency is predicted to increase. It may therefore be more strategic for policy planning for agricultural resilience to explicitly consider differences in soil properties, such as organic matter levels, across counties. For instance, if maize yields in counties with low soil organic matter are particularly vulnerable to drought, it may make more sense to incentivize a transition to crops that are more appropriate to soil and predicted climate conditions in those counties, than to focus exclusively on economic protection through insurance.

Furthermore, while more extensive evidence is needed to understand if the trends we identified at the aggregate-level scale down to the farm, we argue that our findings generally support the notion that large-scale efforts to restore soil organic matter levels at regional/continental scales should improve the resilience of agricultural systems. Such a notion is key to soil health initiatives aimed at increasing agricultural resilience by rebuilding soil organic matter (Bradford *et al* 2019) and initiatives such as 4 ‰ that argue the co-benefits of increased soil organic matter are an important additional incentive to advancing soil carbon sequestration (Lal 2016, Chenu *et al* 2019).

4. Conclusions

Our analyses demonstrate that counties with higher mean soil organic matter content are associated with lower maize yield loss due to drought, that this relationship is strongest under severe drought conditions, and this increased yield protection translates to lower crop insurance payouts under drought conditions. Furthermore, we demonstrate that these impacts are not solely mediated through the impact of soil organic matter on conventional measures of plant available water, but likely occur through additional pathways that influence soil water supply and use by plants, which appear to collectively provide the yield protection benefits we document here. At least at the county level then for US rain-fed maize agriculture, soil organic matter content appears to be an important predictor of resilience to the type of drought conditions that are likely to occur more frequently under future climate scenarios. Further work should investigate whether similar benefits of soil organic matter for yield protection are afforded by agricultural managements that build organic matter in agricultural soils worldwide. In the interim, our analyses highlight the potential value of integrating soil information into resilience planning as agricultural outcomes become more uncertain with the increasing incidence and severity of extreme weather events.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5063/F1M61HN6.

Author contributions

D K, E F, and S W conceived the original project idea. D K and E F developed initial datasets and data processing code. D K and S W developed and verified the analytical methods. All authors contributed to analysis and interpretation of results and development of the final manuscript.

References

Adams R M, Rosenzweig C, Peart R M, Ritchie J T, McCarl B A, Glyer J D, Curry R B, Jones J W, Boote K J and Allen L H 1990 Global climate change and US agriculture *Nature* **345** 219–24

Bates D *et al* 2020 lme4: linear mixed-effects models using "Eigen" and S4 (available at: https://CRAN.R-project.org/package=lme4)

Beaudette D, Roudier P and Brown A 2020 aqp: algorithms for quantitative pedology (available at: https://CRAN.R-project.org/package=aqp)

Bot A and Benites J 2005 Creating drought-resistant soil *The importance of soil organic matter: Key to drought-resistant soil and sustained food production* (*FAO Soils Bulletin* (Rome: Food and Agriculture Organization of the United Nations) (available at: www.fao.org/3/a0100e/a0100e00.htm#Contents)

Bowles T M *et al* 2020 Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America *One Earth* **2** 284–93

Boyle M, Frankenberger W T and Stolzy L H 1989 The influence of organic matter on soil aggregation and water infiltration *J. Prod. Agric.* **2** 290–9

Bradford M A *et al* 2019 Soil carbon science for policy and practice *Nat. Sustain.* **2** 1070–2

Bryant L and O'Connor C 2017 Creating incentives to improve soil health through the federal crop insurance program *Global Soil Security* (*Progress in Soil Science*) ed D J Field, C L S Morgan and A B McBratney (Berlin: Springer) pp 403–9

Carminati A and Javaux M 2020 Soil rather than xylem vulnerability controls stomatal response to drought *Trends Plant Sci.* **25** 868–80

Cassel D K and Nielsen D R 2018 Field capacity and available water capacity *Methods of Soil Analysis* (New York: Wiley) pp 901–26

Chenu C, Angers D A, Barré P, Derrien D, Arrouays D and
    Balesdent J 2019 Increasing organic stocks in agricultural
    soils: knowledge gaps and potential innovations *Soil Tillage
    Res.* **188** 41–52

Craufurd P Q and Wheeler T R 2009 Climate change and the
    flowering time of annual crops *J. Exp. Bot.* **60** 2529–39

Elliott J A and Efetha A A 1999 Influence of tillage and cropping
    system on soil organic matter, structure and infiltration in a
    rolling landscape *Can. J. Soil Sci.* **79** 457–63

Franzluebbers A J 2002 Water infiltration and soil structure
    related to organic matter and its stratification with depth
    Soil Tillage Res. **66** 197–205

Gaudin A C M, Tolhurst T N, Ker A P, Janovicek K, Tortora C,
    Martin R C and Deen W 2015 Increasing crop diversity
    mitigates weather variations and improves yield stability
    PLoS One **10** e0113261

Gelman A 2008 Scaling regression inputs by dividing by two
    standard deviations *Stat. Med.* **27** 2865–73

Han W, Yang Z, Di L and Yue P 2014 A geospatial web service
    approach for creating on-demand cropland data layer
    thematic maps *Trans. ASABE* **57** 239–47

Hayhoe K, VanDorn J, Croley T, Schlegal N and Wuebbles D 2010
    Regional climate change projections for Chicago and the US
    Great Lakes *J. Gt. Lakes Res.* **36** 7–21

Henningsen A 2020 censReg: censored regression (Tobit) models
    (available at: https://CRAN.R-project.org/package=
    censReg)

Hsiao J, Swann A L S and Kim S-H 2019 Maize yield under a
    changing climate: the hidden role of vapor pressure deficit
    Agric. For. Meteorol. **279** 107692

Hudson B D 1994 Soil organic matter and available water capacity
    J. Soil Water Conserv. **49** 189–94

Iizumi T and Wagai R 2019 Leveraging drought risk reduction for
    sustainable food, soil and climate via soil organic carbon
    sequestration *Sci. Rep.* **9** 1–8

Kane Daniel, Bradford Mark, Fuller Emma, Oldfield Emily and
    Wood Stephen KNB 2020 Mean maize yield, soil
    characteristics, and drought metrics for US maize growing
    counties, 2000–2016 (https://doi.org/10.5063/F1M61HN6)

Kuhn M *et al* 2020 caret: classification and regression training
    (available at: https://CRAN.R-project.org/package=caret)

Lado M, Paz A and Ben-Hur M 2004 Organic matter and
    aggregate size interactions in infiltration, seal formation,
    and soil loss *Soil Sci. Soc. Am. J.* **68** 935–42

Lal R 2016 Beyond COP 21: potential and challenges of the '4
    per Thousand' initiative *J. Soil Water Conserv.*
    71 20A–25A

Lefcheck J 2019 Structural equation modeling in R for ecology
    and evolution (available at: https://jslefche.github.
    io/sem_book/index.html)

Lefcheck J, Byrnes J and Grace J 2019 piecewiseSEM: piecewise
    structural equation modeling (available at: https://
    CRAN.R-project.org/package=piecewiseSEM)

Libohova Z, Seybold C, Wysocki D, Wills S, Schoeneberger P,
    Williams C, Lindbo D, Stott D and Owens P R 2018
    Reevaluating the effects of soil organic matter and other
    properties on available water-holding capacity using the
    national cooperative soil survey characterization database *J.
    Soil Water Conserv.* **73** 411–21

Lobell D B, Hammer G L, McLean G, Messina C, Roberts M J and
    Schlenker W 2013 The critical role of extreme heat for maize
    production in the United States *Nat. Clim. Change*
    3 497–501

Lobell D B, Roberts M J, Schlenker W, Braun N, Little B B, Rejesus
    R M and Hammer G L 2014 Greater sensitivity to drought
    accompanies maize yield increase in the U.S. midwest
    Science **344** 516–9

Lu J, Carbone G J and Gao P 2017 Detrending crop yield data for
    spatial visualization of drought impacts in the United States,
    1895–2014 *Agric. For. Meteorol.* **237–238** 196–208

Luber G and McGeehin M 2008 Climate change and extreme heat
    events *Am. J. Prev. Med.* **35** 429–35

Meehl G A *et al* 2007 Global climate projections *Clim. Change*
    3495 747–845

Minasny B and McBratney A B 2018 Limited effect of organic
    matter on soil available water capacity *Eur. J. Soil Sci.*
    69 39–47

National Environmental Public Health Tracking Network 2018
    Standardized precipitation evapotranspiration index,
    1895–2016 *Data Cent. Dis. Control Prev.* (available at:
    https://data.cdc.gov/Environmental-Health-Toxicology/
    Standardized-Precipitation-Evapotranspiration-Inde/
    6nbv-ifib/data)

Oldfield E E, Bradford M A and Wood S A 2019 Global
    meta-analysis of the relationship between soil organic
    matter and crop yields *Soil* **5** 15–32

Pan G, Smith P and Pan W 2009 The role of soil organic matter in
    maintaining the productivity and yield stability of cereals in
    China *Agric. Ecosyst. Environ.* **129** 344–8

Portmann F T, Siebert S and Döll P 2010 MIRCA2000—global
    monthly irrigated and rainfed crop areas around the year
    2000: a new high-resolution data set for agricultural and
    hydrological modeling *Glob. Biogeochem. Cycles* **24** 5

Potter N, Adams J, Stachelek J, Piaskowski J, Sparks A and
    Richardson N 2019 rnassqs: access the NASS "Quick Stats"
    API (available at: https://CRAN.R-project.org/
    package=rnassqs)

R Core Team 2020 R: a language and environment for statistical
    computing (Vienna: R Foundation for Statistical
    Computing (available at: www.R-project.org/)

Reyes J J and Elias E 2019 Spatio-temporal variation of crop loss
    in the United States from 2001 to 2016 *Environ. Res. Lett.*
    14 074017

Sage R F and Kubien D S 2007 The temperature response
    of C3 and C4 photosynthesis *Plant Cell Environ.*
    30 1086–106

Schlenker W and Roberts M J 2009 Nonlinear temperature effects
    indicate severe damages to U.S. crop yields under climate
    change *Proc. Natl Acad. Sci.* **106** 15594–8

Shipley B 2009 Confirmatory path analysis in a generalized
    multilevel context *Ecology* **90** 363–8

Soil Survey Staff 2015 Gridded soil survey geographic (gSSURGO)
    database for the United States of America and the territories,
    commonwealths, and Island Nations served by the
    USDA-NRCS. United States department of agriculture,
    natural resources conservation service *Geospatial Data
    Gatew* (available at: https://gdg.sc.egov.usda.gov/)

Southwest Climate Hub 2018 AgRisk viewer (available at:
    https://swclimatehub.info/rma/rma-data-viewer.html)

Teixeira E I, George M, Herreman T, Brown H, Fletcher A,
    Chakwizira E, De Ruiter J, Maley S and Noble A 2014 The
    impact of water and nitrogen limitation on maize biomass
    and resource-use efficiencies for radiation, water and
    nitrogen *Field Crops Res.* **168** 109–18

The National Drought Mitigation Center 2019a Drought severity
    and coverage index (available at: https://droughtmonitor.
    unl.edu/AboutUSDM/AbouttheData/DSCI.aspx)

The National Drought Mitigation Center 2019b Statistics
    explanation (available at: https://droughtmonitor.unl.
    edu/AboutUSDM/AbouttheData/StatisticsExplanation.
    aspx)

The National Drought Mitigation Center 2019c U.S. drought
    monitor (available at: https://droughtmonitor.unl.edu/)

Urban D, Roberts M J, Schlenker W and Lobell D B 2012
    Projected temperature changes indicate significant increase
    in interannual variability of U.S. maize yields *Clim. Change*
    112 525–33

USDA NASS Staff 2018 USDA—National Agricultural Statistics
    Service—data and statistics (available at: www.nass.
    usda.gov/Data_and_Statistics/index.php)

Vicente-Serrano S M, Beguería S and López-Moreno J I 2009 A
    multiscalar drought index sensitive to global warming: the
    standardized precipitation evapotranspiration index *J. Clim.*
    23 1696–718

Vicente-Serrano S M, Beguería S, Lorenzo-Lacruz J, Camarero J J, López-Moreno J I, Azorin-Molina C, Revuelto J, Morán-Tejeda E and Sanchez-Lorenzo A 2012 Performance of drought indices for ecological, agricultural, and hydrological applications *Earth Interact.* **16** 1–27

Williams A, Hunter M C, Kammerer M, Kane D A, Jordan N R, Mortensen D A, Smith R G, Snapp S and Davis A S 2016 Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: time to invest in soil organic matter? ed JL Gonzalez-Andujar *PLoS One* **11** e0160974

Zhang L-X, Li S-X, Zhang H and Liang Z-S 2007 Nitrogen rates and water stress effects on production, lipid peroxidation and antioxidative enzyme activities in two maize (*Zea mays* L.) genotypes *J. Agron. Crop Sci.* **193** 387–97