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Soil-dependent responses of US crop yields to climate variability and depth to groundwater

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ABSTRACT

The effects of climate variations on crop yield have been widely studied. However, the effects of soil on crop-climate responses are often ignored in crop yield prediction. We investigated the effects of soil texture and soil organic carbon concentration (SOC) on the yield responses of seven major crops (corn, winter wheat, soybean, cotton, barley, oats, rice) to growing season precipitation and temperature between 1958 and 2019 across the conterminous US. We also evaluated the effects of irrigation and groundwater depth on crop-climate responses. Crop yields were most sensitive to precipitation and temperature variability in coarse-textured soils and less responsive to these weather parameters in medium- and fine- textured soils. Increasing SOC concentration (> 2%) contributed to crop yields being less sensitive to precipitation – due to increased water retention, and less responsive to temperature – presumably due to increased buffering capacity against increased water lost through evapotranspiration. Irrigation and an intermediate depth to groundwater increase the resilience of crops to precipitation and temperature changes and these effects were also dependent on soil texture and SOC. To enhance food security for a rapidly growing global population under a changing climate, best management practices should be adopted that improve soil structure and carbon stocks that can increase soil available water storage ("Green Water") and nutrient retention and promote energy conservation. The spatial-temporal variations of soil texture, SOC, and depth to groundwater should be considered in agricultural and ecosystem modeling to more accurately capture crop yield response to climate variations.

1. Introduction

With a rapidly growing global population and increasing demand for food, fiber, feed, and fuel, producers are under significant pressure to produce crops with a higher yield using limited water, nutrients, and energy supplies (Dodds and Bartram, 2016; Schyns et al., 2019). It has been well established that the deviation of precipitation and temperature from expected or climatic averages often cause yield reductions (Kucharik and Ramankutty, 2005; Kucharik and Serbin, 2008; Schlenker and Roberts, 2009; Licker et al., 2010; Schlenker and Lobell, 2010; Lobell et al., 2011; Hsiang et al., 2013; Burke and Emerick, 2016). For example, shortage of precipitation during the crop growing season can lead to yield reduction ((Hanjra and Qureshi, 2010)Lobell et al., 2014) while temperatures above average can lead to crop heat stress and yield loss (Long and Ort, 2010; Jha et al., 2014).

The dependence of crop yields on climate has long been incorporated in various crop growth models to predict yield sensitivity to varying climate conditions (e.g. Hodges et al., 1987; Jagtap et al., 2002; Kucharik, 2003; Keating et al., 2003; Srinivasan et al., 2010; Dzotsi et al., 2013). Long-term measurements of crop-climate interactions have also been used to evaluate the impacts of climate change on food security (Schmidhuber and Tubiello, 2007; Brown and Funk, 2008; Lobell et al., 2008; Wheeler and Von Braun, 2013), and economic (Iizumi et al., 2018) and societal (Carleton, 2017) disruptions across the world.

Apart from precipitation and temperature, crop yields are also dependent on soil properties such as soil texture (Warrick and Gardner, 1983; Nouri et al., 2016; Butcher et al., 2018), carbon stocks (Lal, 2004; Stockmann et al., 2013; Osanai et al., 2020), nutrient availability (Schmidt et al., 2002; Tan et al., 2005), soil water storage – known as the "Green Water" (Schyns et al., 2019), as well as root water uptake and depth to groundwater table (Soylu et al., 2014, 2017), and socioeconomic factors (Ramankutty et al., 2006). Although soil properties vary greatly in space (Warrick and Gardner, 1983; Sanchez et al., 2009), the interactions between soil properties and crop yields are not well

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quantified across large spatial extents with varying climate conditions.

The effects of soil texture on crop yield are convoluted and affected by climate conditions. Fine-textured soils (e.g. silty loams) often have a high water holding capacity and more resistance (smaller saturated hydraulic conductivity) to plant water uptake in wet conditions compared to coarse-textured soils (e.g. sandy loam) (Or and Lehmann, 2019). Fine-textured soils can be poorly drained and susceptible to waterlogging, which can lead to denitrification and yield loss (Delin and Berglund, 2005). Under unsaturated conditions (water limited environment), fine-textured soils have a higher water retention (e.g. higher suction due to finer pore spaces) and a larger unsaturated hydraulic conductivity than coarse-textured soils. Crops grown in fine-textured soils may be less sensitive to drought compared to coarse-textured soils if the climatic conditions are similar (He et al., 2013).

Soil texture affects the responses of crop yield to irrigation or groundwater supply. Due to the low water holding capacity, frequent irrigation is required in coarse-texture soils during the growing season, particularly when evapotranspiration is high (Huang and Hartemink, 2020). Soil texture affects crop yield when a shallow groundwater table is present and the optimum groundwater table depth is found shallower in coarse-textured soils than fine-textured soils (Zipper et al., 2015).

Soil organic carbon (SOC) is another important factor as it has the potential to increase soil structure (e.g. aggregate stability) (Bronick and Lal, 2005), and water and nutrient (e.g. nitrogen) retention in soils (Karhu et al., 2011). The global initiative, "Soil Carbon 4 per Mille", has been proposed to increase SOC sequestration at a rate of 4 per mille in the top 1 m of global agricultural soils (2–3 Gt C per year), aiming to offset 20–35% of global anthropogenic greenhouse gas emissions (Minasny et al., 2017). Studies have found that increasing SOC stock can increase soil quality (e.g. water retention, aggregation, cation exchange capacity) and improve crop yield (Lal, 2006; Williams et al., 2016; Yost and Hartemink, 2019).

However, it remains unknown how the variations of soil (e.g. texture, SOC) play a role in the location-specific crop-climate responses, particularly across large spatial extents with diverse climate gradients. In this study, we hypothesize that soil texture and SOC have distinct effects on the crop yield responses to growing season precipitation and temperature and the effects vary with crop types, irrigation management (irrigation vs. rainfed), and depth to groundwater table across large spatial scales. We test these hypotheses by performing spatial-temporal analysis of long-term (1958–2019) county-level yield datasets across the conterminous US (CONUS) of major field crops (e.g. corn, wheat, soybean, cotton, barley, oats, rice) and high-resolution (4-km) climate reanalysis data. We expect that this empirical analysis can provide useful information for modelers to evaluate the existing models on crop yield responses to climate variation across different soil types), irrigation management and groundwater condition as well as inform university extension personnel and stakeholders for decision-making on sustainable agricultural production and natural resources conservation.

2. Materials and methods

2.1. Yield data

Crop yield data were collected from the USDA National Agricultural Statistics Service (NASS) (https://quickstats.nass.usda.gov/). The data were aggregated at the county level and on a yearly basis from 1958 to 2019. Several staple field crops were selected, including corn (grain), winter wheat, soybean, cotton, barley, oats, and rice. For corn, wheat, soybean and cotton, yield data were available from irrigated, non-irrigated (rainfed), and combined fields. Combined fields meant that information on whether the irrigation was used was not available. For Barley, oats, and rice, only combined yield datasets were available. The original units of the yields were retained, namely bushel per acre (bu ac^{-1}) for corn, wheat, soybean, barley, oats and pounds per acre (lb ac^{-1}) for cotton and rice. For each crop type, we excluded the counties that had annual yield observations fewer than 15 and excluded counties that had zero yields. The summary statistics of yield data and corresponding soil properties are shown in Appendix Table 1.

2.2. Cropland maps

A cropland map was obtained from the USDA National Agricultural Statistics Service Cropland Data Layer ((USDA National Agricultural Statistics Service Cropland Data Layer, 2017)). The map was available at 30-m resolution and represented main crop types across the CONUS in 2017. A map of irrigated crop fields was obtained from the MODIS-derived product (Brown et al., 2019), which had a spatial resolution of 250 m and represented its distributions across the CONUS in 2017.

2.3. Climate data and crop growing season dates

Mean monthly precipitation and maximum and minimum temperature data from 1958 to 2019 were collected from Terraclimate (Abatzoglou et al., 2018), which covers the globe at approximately 4 km resolution. Climate data were averaged for each US county to be paired with the county-level yield data. Mean temperature were estimated using the monthly averages of the maximum and minimum temperature data.

Maps of crop growing season dates were collected from the Crop Calendar Dataset of the University of Wisconsin, Center for Sustainability, and the Global Environment (SAGE) (Sacks et al., 2010). The dataset was available at 5 arc min resolution across the globe. In this study, growing seasons of different crops were defined between the first day of the planting and the last day of the harvest. Afterward, we selected the months within the growing seasons to calculate the mean precipitation and minimum, maximum, mean and range of temperature during the growing seasons on a yearly basis for different crops. For winter wheat, climate data would cover two consecutive years. To simplify the modeling process and make our results comparable across different crops, we did not consider snowfall as precipitation for winter wheat. The effect of soil freezing on crop growth mainly depends on soil temperature as a function of air temperature, soil thermal conductivity and heat capacity (controlled by soil texture and SOC), which is difficult to quantify and not directly evaluated here. Instead, we used minimum growing season air temperature as a proxy of soil freezing to evaluate the effect of temperature on crop yield within different soil types.

2.4. Soil data

Soil clay and sand content and soil organic carbon (SOC) concentration data were collected from the OpenLandMap (Hengl, 2018a, 2018b; Hengl and Wheeler, 2018). The maps were generated using soil profile data from the world with machine learning algorithms and were available at 250-m resolution. Maps of soil properties from depths of 0, 10, 30, and 60 cm were used to estimate the depth-weighted soil properties at 0–60 cm interval using the trapezoidal rule:

$$\mathrm{Soil}_{0-60\ \mathrm{cm}} = \frac{\left[(\mathrm{Soil}_{0\ \mathrm{cm}} + \mathrm{Soil}_{10\ \mathrm{cm}}) \times 10 \times 0.5\right] + \left[(\mathrm{Soil}_{10\ \mathrm{cm}} + \mathrm{Soil}_{30\ \mathrm{cm}}) \times 20 \times 0.5\right] + \left[(\mathrm{Soil}_{30\ \mathrm{cm}} + \mathrm{Soil}_{60\ \mathrm{cm}}) \times 30 \times 0.5\right]}{60} \quad (1)$$

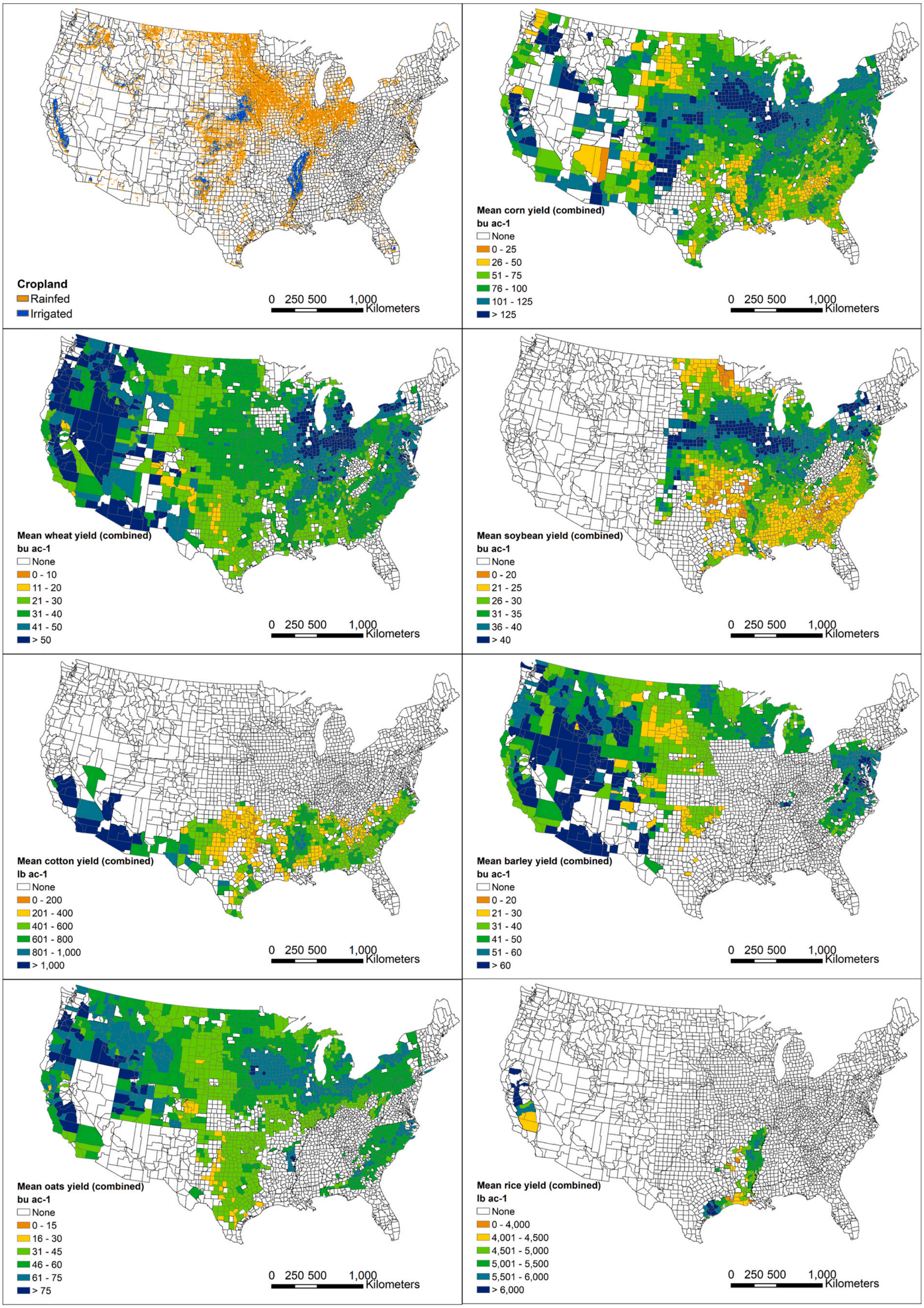

Fig. 1. Spatial distribution of cultivated cropland (irrigated and rainfed) from Brown et al. (2019) and major field crops from (USDA National Agricultural Statistics Service Cropland Data Layer, 2017) with rainfed and irrigated fields combined in 2017 including corn (grain), winter wheat, soybean, cotton, barley, oats, and rice across the conterminous US (CONUS).

The depth of 60 cm for soil properties was selected to represent the effective rooting depth for most field crops. Soil texture classes were estimated using the soil clay and sand content at 0–60 cm using the USDA Soil Texture Triangle using the R software (version 3.6.1) with the "soiltexture" package (version 1.5.1, Moeys and Shangguan, 2011). Soil texture classes were grouped into three classes including fine-textured (Silty loam, silty clay loam, silty clay), medium-textured (loam, and clay loam), and coarse-textured soils (sandy loam, sandy clay loam, loamy sand, sand) across the US. The grouping of soil texture into these classes was based in the order of the available water capacity of the soils given the role of soil texture class on water retention and movement (Or and Lehmann, 2019). SOC concentrations were classified into low (<2%) and high (>2%) based on their distribution across the US and previous studies on the effects of SOC on water retention (Rawls et al., 2003).

2.5. Hydrological data

A map of simulated groundwater table depth from long-term groundwater table observations (data collected during 1927–2009 across the US) (Fan et al., 2013) was obtained from Fan et al. (2017) and Aquanow (2020) which has a spatial resolution of 1 km. A map of estimated soil drainage class was obtained from the "matchclover" of the Forage Information System from the Oregon State University (https://forages.oregonstate.edu/matchclover/soils). The groundwater table depth data were used to account for varied plant root water uptake under different groundwater depths because of the importance of plant root distribution and root water compensation on plant productivity (Soylu et al., 2014, 2017). The soil drainage class dataset was used for interpreting results.

2.6. Spatial-temporal analysis

We followed the previous study by Hsiang et al. (2013) to calculate the effects of climate and soil on crop yields from 1958 to 2019 for different counties across the US. In brief, the following statistical models were used to describe the response of crop yield to climate change:

$$Y_{i,t}^{k} = g^{k}\left(P_{i,t}^{k}\right) + f^{k}\left(T_{i,t}^{k}\right) + f^{k}\left(T_{i,t}^{k}\right) + \mu_{i}^{k} + \gamma_{t}^{k} + \epsilon_{i,t}^{k} \tag{2}$$

where $Y_{i,t}^{k}$ was the natural log-transformed yield of crop k for county i in year t. We log-transformed the crop yield to model the yield response to climate variations for two reasons: 1) the relationships between climate variables and crop yield are often not linear (Hsiang et al., 2013); 2) several crop yields were moderately or strongly skewed (e.g. barley: skewness = 1.01; corn-rainfed: skewness = 0.77; wheat-rainfed: skewness = 1.30). $P_{i,t}^{k}$ and $T_{i,t}^{k}$ were the crop growing season mean precipitation and minimum, maximum, mean or range of temperature for county i in year t; g^{k} and f^{k} represented the fixed effects of precipitation and temperature on the crop yield; μ_{i}^{k} and γ_{t}^{k} represented the fixed effects of county and year on the crop yield. It was expected that agricultural management (e.g. irrigation, fertilization, pest control, crop varieties) varied across counties and changed over time which could be accounted

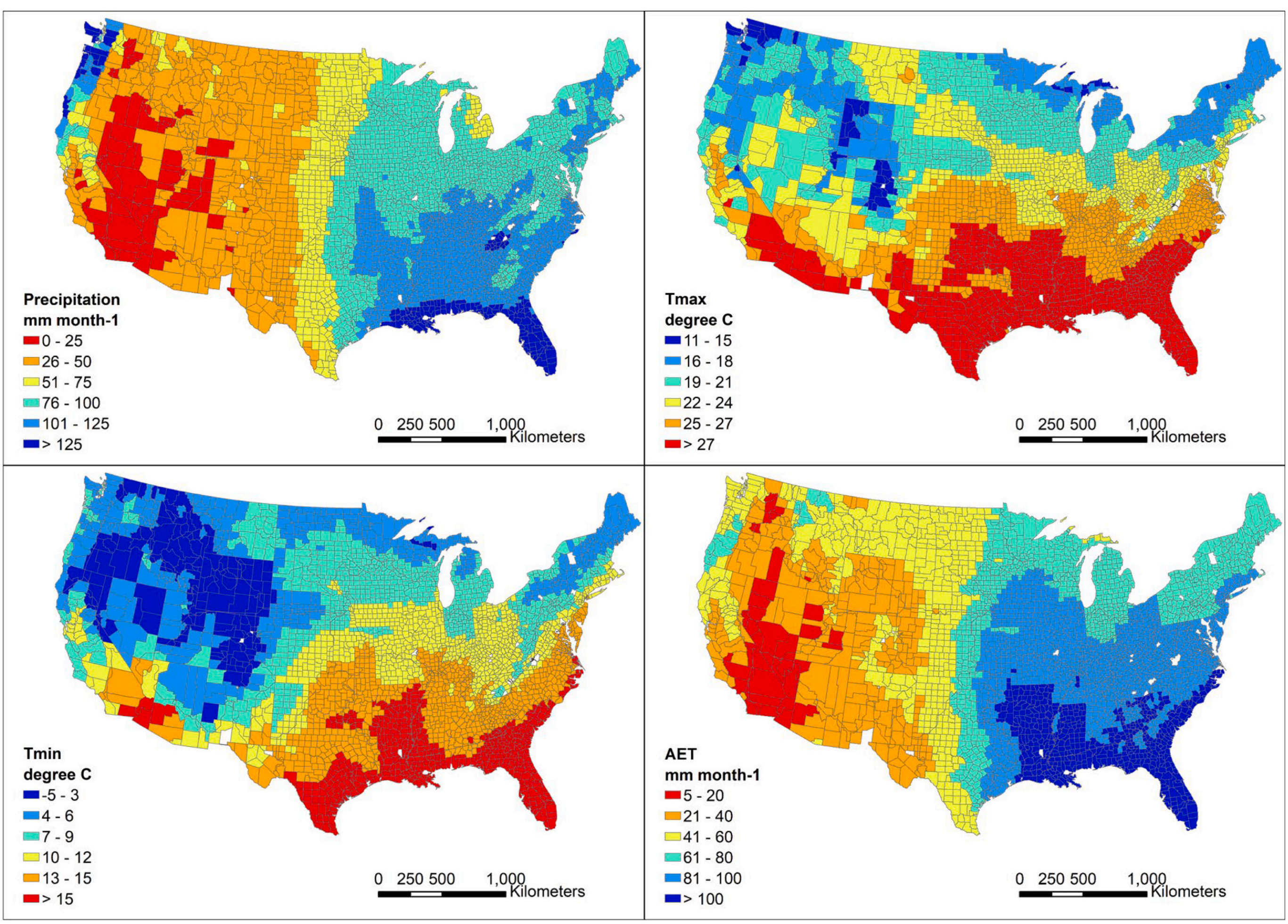

Fig. 2. Spatial distribution of long-term growing season (May to November) mean precipitation (mm month^{-1}), maximum (Tmax) and minimum (Tmin) temperature (°C), actual evapotranspiration (AET, mm month^{-1}) across the conterminous US (CONUS). The data were obtained from TerraClimate (Abatzoglou et al., 2018).

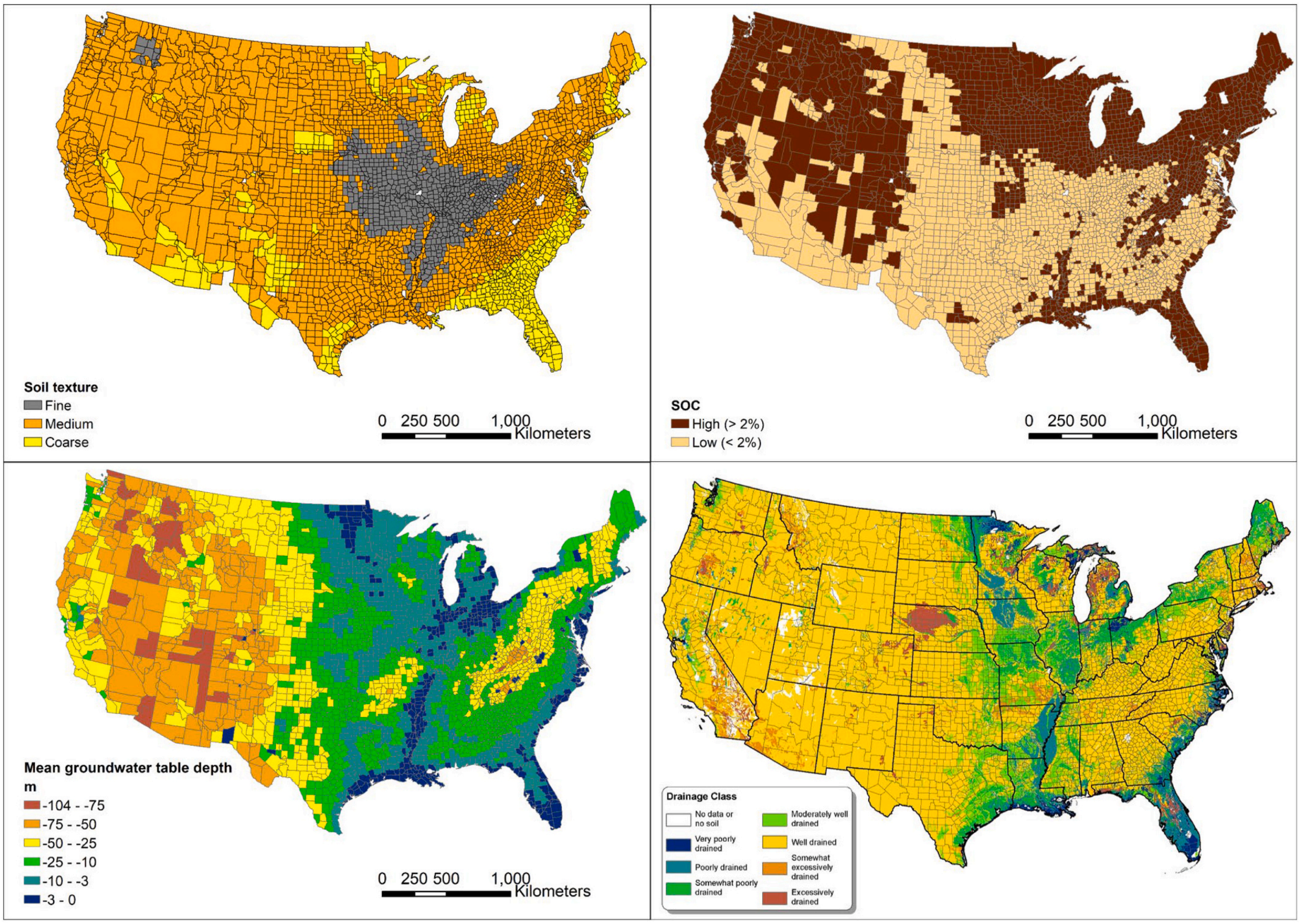

Fig. 3. Spatial distribution of estimated soil texture (0–60 cm), soil organic carbon (SOC) concentration and long-term groundwater (GW) table depth and soil drainage class across the conterminous US (CONUS). Soil maps were obtained from Hengl (2018a, 2018b) and Hengl and Wheeler, 2018; groundwater table depth was from Fan et al. (2013); soil drainage map was obtained from the Forage Information System in the Oregon State University (https://forages.oregonstate.edu/matchclover/soils).

for by the fixed effects. $\epsilon_{i,t}^{k}$ was the residual, representing the noise of the data. In this model, mean crop growing season precipitation and minimum, mean, and maximum temperature were binned into 20 mm month^{-1} and 2 °C intervals, respectively, with 1 °C for range of temperature to account for the non-linear response between crop yield and climate variables.

In this study, we did not consider the correlations/covariance between precipitation and temperature because the variance inflation factors calculated from the linear models showed scores less than 1.2. The scores were calculated using the “vif” function from the R “car” package (Fox et al., 2012). This indicated that the multi-collinearity was minimal in the linear models (Shieh, 2011). To study the interactions between precipitation and temperature, we split the yield datasets into different climate regimes (see below).

To investigate the effects of soil texture and/or SOC on the climate-yield interactions (i.e. g^k and f^k values for each crop type), different statistical models (Eq. 2) were fitted using subsets of county-level climate and yield data grouped based on soil texture and/or SOC classes (e.g. counties with fine-, medium-, and coarse- textured soils were fitted using different models). In this study, we fitted the models with four scenarios:

1) fitting different models using different subsets of the climate-yield datasets categorized by soil texture classes (fine-, medium-, and coarse-) without considering variations in SOC;

2) fitting different models using different subsets of the climate-yield datasets categorized by soil texture classes and when SOC was higher than 2% (high SOC) and lower than 2% (low SOC);

3) fitting different models using different subsets of the climate-yield datasets categorized by three soil texture classes and when groundwater table depth was deeper than 3 m (deep GW table depth) and shallower than 3 m (shallow GW table depth); to simplify the modeling process, a uniform cutoff depth of 3 m was selected because field crops can have a maximum root depth to 1.5–1.8 m (Klepper, 1991; Fan et al., 2016) and the extinction depth (depth limit for evapotranspiration from groundwater) has been found to range from 1.45 m in sands to 4.3 m in silty clay (Shah et al., 2007). This scenario was selected to evaluate the effect of soil texture on the dependence of climate-yield interactions on shallow groundwater table.

4) fitting different models using different subsets of the climate-yield datasets categorized by two SOC concentrations (high vs. low) and when groundwater table depth was deeper than 3 m (deep GW table depth) and shallower than 3 m (shallow GW table depth). This scenario was selected to evaluate the effect of SOC on the dependence of climate-yield interactions on shallow groundwater table.

All of the four scenarios mentioned above included 15 subsets of crop-specific yield datasets: corn (grain), winter wheat, soybean and cotton that were measured in rainfed, irrigated and combined fields (4 crops × 3 types of management), and barley, oats, and rice measured in fields without information about management. According to our preliminary analysis (see Appendix for details), crop-climate responses

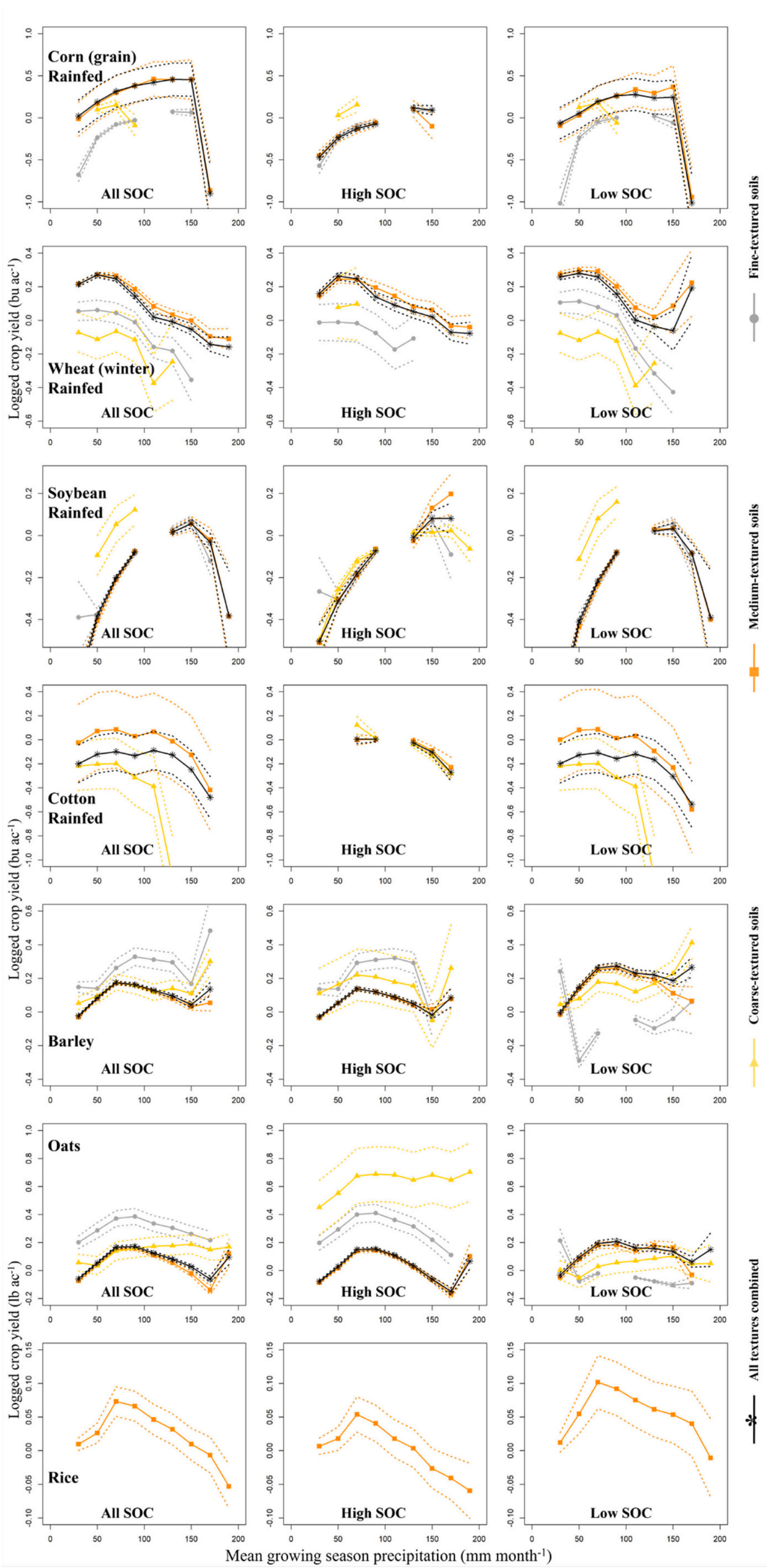

Fig. 4. Soil-dependent crop yield responses to mean growing season precipitation (binned by 20 mm month^{-1}) across different soil texture classes (fine, medium, coarse and all combined) with all SOC levels, and high (> 2%) and low (<2%) SOC concentrations. Note: corn (grain), winter wheat, soybean and cotton were from rainfed (non-irrigated) fields. The solid and dashed lines represent the estimated coefficients and ± standard errors of the fixed effect (precipitation) on crop yields, respectively.

from the combined fields were different from those observed from either rainfed or irrigated fields, which was caused by the mixing of rainfed and irrigation water management.

The model fitting was done using the "lm" function of R package (version 3.5.1) via the ordinary least square method for parameter estimation. Both the estimated coefficients of the fixed effects (e.g. g^k and f^k for precipitation and temperature, respectively) and their standard errors were calculated. We considered the precipitation and temperature values to be optimal for crop growth when the estimated coefficients of the fixed effects (i.e. g^k and f^k) reached global maximum values within the observed ranges.

3. Results

3.1. Spatial distributions of croplands and soil properties across the CONUS

The spatial distribution of cultivated cropland in 2017 across the CONUS is shown in Fig. 1. Non-irrigated (rainfed) lands are concentrated in the central US, comprising the US Midwestern region and other key growing regions in the eastern and western US. Irrigated croplands are primarily distributed along the Mississippi River with minor fragments sparsely distributed across the western US (e.g. Central Valley of California) and Great Plains region (e.g. Nebraska and Kansas).

The spatial distributions of major field crops and long-term (1958–2019) mean county-level crop yields (irrigated and rainfed fields combined) also are presented in Fig. 1. Corn (grain) and soybean are often in rotation and mainly distributed in eastern US with the highest mean yields within the US Midwestern region. Winter wheat is widely grown across the entire CONUS with the highest yields found close to the Great Lakes and in western US. Barley and oats are mainly grown in northern US and along the western and eastern coasts with the highest yields in western US, Great Lakes, and eastern coasts. Cotton is mostly grown in the southern US with the highest yields in southwestern US. Rice is primarily distributed in California and along the Mississippi River in the southern US.

Long-term (1958–2019) growing season (May to November) mean precipitation and actual evapotranspiration (AET) display longitudinal patterns, increasing from western US to eastern US and northwestern coast (Fig. 2). Maximum and minimum growing season temperatures decrease from south to north across the CONUS, primarily following a latitudinal trend. In terms of soil texture classes (mean values within 0–60 cm depth) (Fig. 3), most US counties are characterized by intermediate-textured soils (i.e. loam and clay loam), with fine-textured soils (i.e. silty loam and silty clay loam) located in the eastern US and coarse-textured soils (i.e. sandy loam, sandy clay loam, loamy sand, and sand) along the eastern coast and southern borders. Mean SOC concentration (0–60 cm) is generally higher than 2% in the northeast and northwest CONUS, as well as in southeastern states, and it is lower than 2% in remaining areas.

The distribution of long-term mean groundwater (GW) table depth is similar to precipitation, increasing from eastern (humid/semi-humid regions) to western (arid/semi-arid) US (Fig. 3). Particularly, shallow groundwater tables are identified close to the Great Lakes and Mississippi River and along the eastern coasts. The distribution of soil drainage class is consistent with soil texture classes where poorly drained soils are associated with fine-textured soils and vice versa (Fig. 3).

3.2. Effects of soil texture on the yield responses to growing season precipitation

With increasing precipitation during the growing season, all crops experienced increasing yields as precipitation increased, and then started to decline once reaching their maximum yield values (Fig. 4). The optimal growing season mean precipitation values ranged from 40 to 140 mm month^{-1} (Table 1) and varied with crop types: corn (rainfed, 100–140 mm month^{-1}) ≈ soybean (rainfed, 120–140 mm month^{-1}) > barley (80–140 mm month^{-1}) > oats (60–120 mm month^{-1}) ≈ rice (60–100 mm month^{-1}) ≈ cotton (rainfed, 40–100 mm month^{-1}) > wheat (rainfed, 20–80 mm month^{-1}).

Although the optimal precipitation did not vary significantly across soil texture classes, crop yield response to precipitation was affected by soil texture. Corn, wheat, and cotton yields were most sensitive to precipitation change in medium-textured soils (marked in orange), followed by coarse-textured (yellow) and fine-textured (grey) soils (Fig. 4). For example, when precipitation increased from 50 to 100 mm month^{-1}, log-transformed corn yields increased from 0.2 to 0.4 bu. ac^{-1} in medium-textured soils. By comparison, log-transformed corn yields only increased from −0.25 to 0 bu. ac^{-1} in fine-textured soils (negative log-yield indicated the increase was smaller than positive log-yield).

Different patterns of the soil texture effect were observed for barley and oats, where yields in fine-textured soils (grey) are most sensitive to precipitation change, followed by coarse-textured (yellow) and medium-texture (orange) soils. For example, when growing season mean precipitation increased from 50 to 100 mm month^{-1}, log-transformed barley yields increased from 0.15 to 0.30 bu. ac^{-1} in fine-textured soils but only increased from 0.10 to 0.15 bu. ac^{-1} in coarse- and medium- textured soils.

Soybean (rainfed) yields in different soil textures had similar sensitivity to precipitation change, despite the fact that coarse-texture soils were more sensitive to precipitation changes under low precipitation conditions (40–80 mm month^{-1}, no sufficient observations for yield under high precipitation conditions). The soil texture effects on rice yield is unclear because county-level yield observations were not available in coarse- and fine- texture soils.

When all soil textures were combined, the responses curves (marked in black) were similar to those of the medium-texture soils (orange). Therefore, the effects of soil texture might be overlooked in previous crop-climate response studies which did not consider soil texture classes differently. It should also be noted that these response curves only indicated the sensitivity of soils to precipitation change, not the absolute differences of crop yields among soil texture classes, which were accounted for by the intercepts of the linear models and would not be discussed here (see Methods Section).

3.3. Effects of soil texture on the yield responses to growing season temperatures

The responses of crop yields to maximum growing season temperature is presented in Fig. 5. Corn (rainfed), wheat (rainfed), barley, and oats showed maximum yields at optimal temperature and the yields started to decline as temperatures increased further. The optimal maximum growing season temperature ranged from 6 to 34 °C (Table 1) and varied with crop types: corn (rainfed, 18–20 °C) > barley (16–20 °C) ≈ oats (16–20 °C) > wheat (rainfed, 6–24 °C). Soybean (rainfed) and cotton (rainfed) yields tend to decline with increasing maximum temperature from 20 to 30 °C but showed increased yields at extreme high temperatures (>30 °C). Rice yields increased with increasing maximum growing season temperature and reached the optimal temperature at 28–30 °C within the observed ranges.

Similarly, although the optimal temperatures did not vary significantly across soil texture classes, responses of crop yields to temperature change were also affected by soil texture. However, different patterns were observed for soil texture compared to precipitation. Yields of corn (rainfed), soybean (rainfed), cotton (rainfed), and barley were most sensitive to temperature change in coarse-textured soils, followed by medium-textured soils, and least sensitive in fine-textured soils (Fig. 5). For example, when maximum temperature increased from 20 to 30 °C, log-transformed corn yields decreased from 0.1 to −0.8 bu. ac^{-1} in coarse-textured soils. By comparison and for the same temperature change, log-transformed corn yields only decreased from −0.2 to −0.7

Table 1
Summary of optimal monthly averaged precipitation (mm month^{-1}), maximum (Tmax), minimum (Tmin), and mean (Tmin) temperature (°C) for corn (rainfed), winter wheat (rainfed), soybean (rainfed), cotton (rainfed), barley, oats and rice in different soil texture classes. Note: N.A. indicates insufficient crop yield measurements.

Crop	Precip. (mm month^{-1})			Tmax (°C)			Tmin (°C)			Tmean (°C)		
	Fine-textured	Medium-textured	Coarse-textured	Fine-textured	Medium-textured	Coarse-textured	Fine-textured	Medium-textured	Coarse-textured	Fine-textured	Medium-textured	Coarse-textured
Corn	100–140	100–140	N.A.	18–20	18–20	18–20	14–16	0–4	4–8	12–14	12–14	12–14
Wheat (winter)	20–80	20–80	20–80	10–24	6–10	10–24	0–8	14–16	12–16	6–8	2–4	2–4
Soybean	120–140	120–160	N.A.	24–26	24–26	28–30	6–8	6–8	6–8	18–20	16–18	N.A.
Cotton	N.A.	40–100	40–60	N.A.	24–26	32–34	N.A.	4–6	4–6	N.A.	16–18	16–18
Barley	80–140	60–100	60–100	18–20	16–20	16–20	2–6	0–6	2–6	8–10	8–10	12–14
Oats	60–120	60–120	60–160	18–26	16–20	16–20	2–4	0–4	0–4	10–12	8–10	8–10
Rice	N.A.	60–100	N.A.	N.A.	28–30	N.A.	N.A.	6–8	N.A.	N.A.	16–18	N.A.

bu. ac^{-1} in fine-textured soils.

This was not the case for winter wheat and oats. Winter wheat yields were most sensitive to change in maximum growing season temperature in fine-textured soils, followed by coarse-textured soils, and least sensitive in medium-textured soils. Oat yields were most sensitive to a change in maximum growing season temperature in medium-textured soils, followed by fine-textured soils and then coarse-textured soils. Again, it should be noted that the curves did not represent the absolute differences of yields among soil textures.

The responses of crop yields to minimum, mean and range of growing season temperature were also calculated (see Appendix Figs. 3–8 for details). In general, similar patterns were observed while the effects of soil texture were weaker than those observed for maximum temperature. It was also noted that all the crops (except for rice) achieved maximum yields when the ranges of growing season temperatures were relatively small.

3.4. Effects of SOC on yield responses to precipitation and temperature

Crop yield response to precipitation and temperature were also affected by SOC concentrations. In terms of growing season precipitation, increasing SOC from low concentration (<2%) to high concentration (>2%) generally made crop yields less sensitive to precipitation decreases (curves with smaller slope shown in Fig. 4). For example, when precipitation decreased from 120 to 40 mm month^{-1}, log-transformed winter wheat (rainfed) yields decreased from 0.25 to 0.15 bu. ac^{-1} in medium-textured soils and 0 to −0.15 bu. ac^{-1} in fine-textured soils with high SOC. Under low SOC conditions, the decrease was greater and from 0.25 to 0.05 bu. ac^{-1} in medium-textured soils and from 0.1 to −0.15 bu. ac^{-1} in fine-textured soils. The "buffering" effect of SOC was also observed for corn (rainfed), soybean (rainfed), cotton (rainfed), barley, and oats. It was also noted that the "buffering" effect of SOC was stronger in coarse-textured soils compared with fine- and medium- textured soils.

Similar patterns were observed for crop-temperature responses under varying SOC concentrations. In general, increasing SOC from low concentration (<2%) to high concentration (>2%) made crop yields less sensitive to temperature changes during the growing seasons (Fig. 5 and Appendix). For example, when maximum growing season temperature increased from 18 to 28 °C, log-transformed corn (rainfed) yields decreased from approximately 0 to −0.8 bu. ac^{-1} in coarse-, medium, and fine- textured soils under low SOC condition. Under high SOC condition for same increase of maximum temperature, log-transformed corn yields only decreased from 0 to −0.4 bu. ac^{-1} in medium- and fine- textured soils (no data for coarse-textured soils). The effects of SOC were also observed for wheat (rainfed), soybean (rainfed), barley, and oats with coarse-textured soils more responsive to maximum temperature increases than fine- and medium- textured soils.

3.5. Effects of irrigation on yield responses to precipitation and temperature

The effects of irrigation on crop-yield responses were also studied. In general, when the fields were irrigated, the responses of crop yields (corn, wheat, soybean, and cotton) became less sensitive to changes in growing seasons precipitation and temperature compared to the responses observed under rainfed conditions (refer to Appendix Figs. 1, 2, 4 and 6).

3.6. Soil-dependent effects of groundwater table depth on crop-climate response

The effects of groundwater table depth on the yield responses to precipitation and temperature and their dependence on soil texture are presented in Fig. 6. Three main features are worth reporting. Firstly, when fine- and medium- textured soils have a shallow groundwater

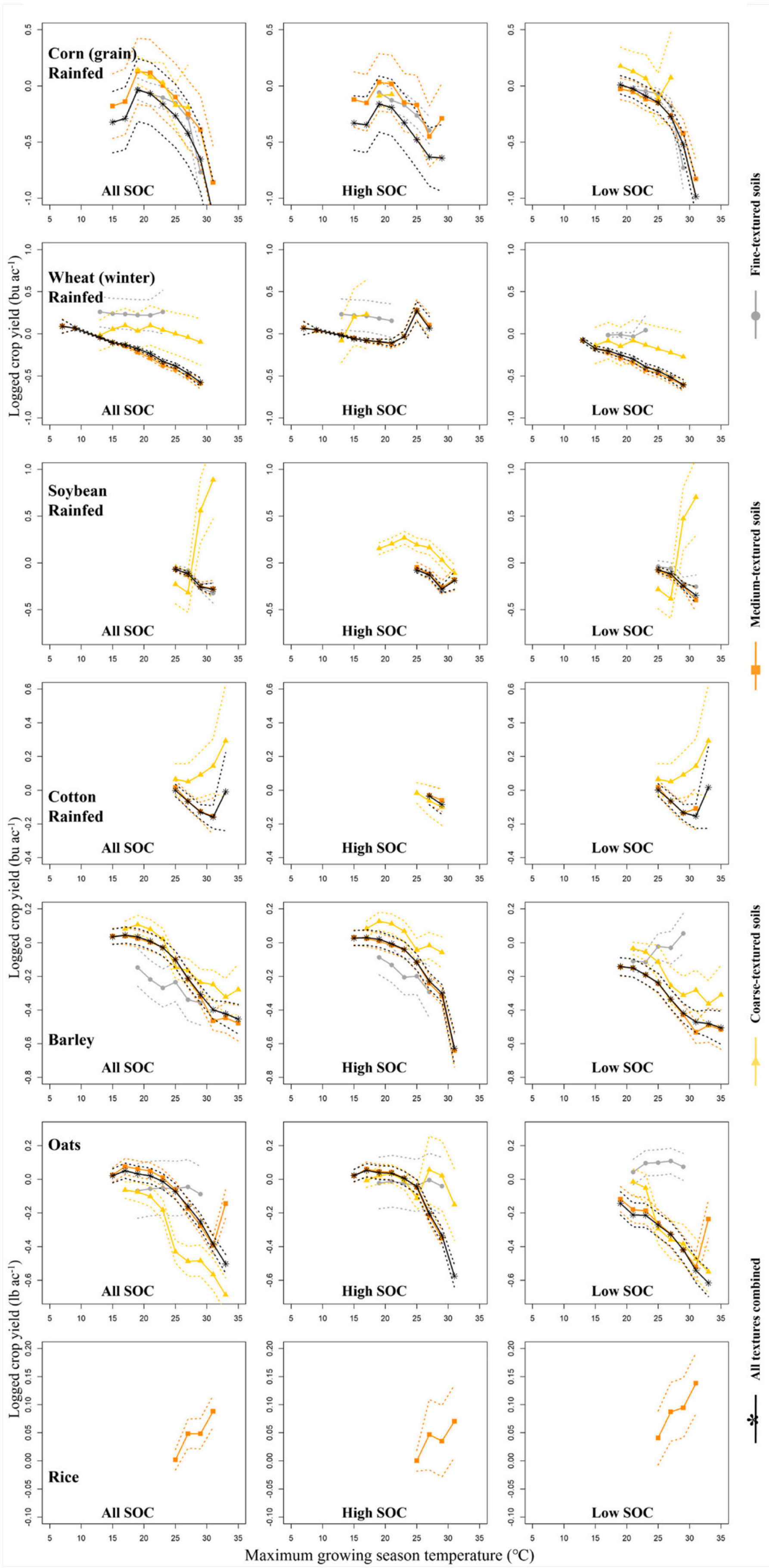

Fig. 5. Soil-dependent crop yield responses to maximum growing season temperature (binned by 2 °C) across different soil texture classes (fine, medium, coarse and all combined) with all SOC levels, and high (> 2%) and low (<2%) SOC concentrations. Note: corn (grain), winter wheat, soybean and cotton were from rainfed (non-irrigated) fields. The solid and dashed lines represent the estimated coefficients and ± standard errors of the fixed effect (maximum temperature) on crop yields, respectively.

table depth (<3 m), crop yields were relatively insensitive to precipitation change compared to those soils with a deep groundwater table depth (>3 m). Secondly, when fine- and medium- textured soils have a shallow groundwater table depth, crop yields were also relatively insensitive to (maximum) temperature change compared to locations with a deep groundwater table depth. Thirdly, coarse-textured soils were most sensitive to precipitation and temperature changes during the growing season regardless of the depth to groundwater table.

Distinct features were also found for the effects of groundwater table depth on the yield responses to precipitation and temperature and their dependence on SOC concentrations (Appendix Fig. 9). Firstly, when soils have a shallow groundwater table depth (<3 m), regardless of SOC concentrations, crop yields were insensitive to precipitation change compared to those soils with a deep groundwater table depth (>3 m). Secondly, when soils have a shallow groundwater table depth, regardless of SOC concentrations, crop yields were also relatively insensitive to (maximum) temperature change compared to those with a deep groundwater table depth. Thirdly, soils with high SOC concentrations were less sensitive to precipitation and temperature changes during the growing seasons compared to soils with low SOC concentrations regardless of the depth to groundwater table.

4. Discussion

4.1. Soil texture effect on crop-precipitation responses

The potential causes of soil-dependent effects on crop yield responses to climate across the continental US are discussed here. As shown in Table 2, when SOC is low (<2%), field capacity is highest in fine-textured soils (0.48–0.49), followed by medium-textured soils (0.45–0.48), and coarse-textured soils (0.20–0.40). This leads to differences of crop yields in different soil texture classes. When growing season precipitation is high (>100 mm month^{-1}), fine- and medium-textured soils can store more available water due to the large field capacity (a larger fraction of water exists as capillary water, Hillel, 2012) for crops to achieve high yields at the national-scale while coarse-textured soils are less affected due to the small field capacity (a larger fraction of water exists as less available gravitational water) (Fig. 4). Similarly, when precipitation decreases (e.g. occurrence of drought), fine- and medium- textured soils retain more water due to a larger plant available water capacity and show resistance of crop yield decline at the national-scale to decreasing precipitation (<80 mm month^{-1}). The results from our national-scale analysis are consistent with previous field-scale observations. For example, Arora et al. (2011) reported higher soybean yield in sandy loam than loamy sand and attributed that to differences in plant available water (Arora et al., 2011). Similarly, Guo et al. (2012) found that soil texture classes were statistically correlated to cotton yield, possibly due to the differences in water and nutrient holding capacities of different soils (Guo et al., 2012). This was also confirmed by Tremblay et al. (2012), where corn yields were significantly greater in fine-textured soils (silty loams) than coarse-texture soils (sandy loam and loamy sand).

In terms of the crop yield sensitivity, medium-textured soils have a higher sensitivity than fine-textured soil in response to precipitation at the national-scale (Fig. 4). This may be because medium-textured soils have a higher plant available water capacity (termed “green water”) than fine-textured soils. This was also reported in Arvidsson (1998), where an increasing of soil silt content rather than clay content was consistent with increased cotton yield (medium-textured soils with high silt content have a higher plant available water capacity).

The soil texture effects vary with crop types. Soybean (rainfed) has a higher sensitivity to precipitation in coarse-textured soils (Fig. 4), while corn has the highest sensitivity in medium-textured soils. This is possibly because corn is a C4 plant but soybean is a C3 plant, and demand for water/evapotranspiration is often higher for corn than soybean (Allen et al., 1998). Tremblay et al. (2012) reported that corn yield was more sensitive to precipitation and added nitrogen fertilizers in fine-textured soils (silty loams) than coarse-texture soils (sandy loam and loamy sand). This was partly confirmed in our analysis (grey and yellow lines in Fig. 4) and more measurements were needed to further conform this across a wider range of precipitation. Winter wheat (rainfed) yield peaks at lower monthly precipitation and then declines. As shown in Appendix Fig. 10, winter wheat performed best in cold and dry regimes, followed by warm and dry regimes, warm and wet regimes, and performed worst in cold and wet regimes. This is possibly because high precipitation in early growing seasons can delay planting in fall and reduce fall stand establishment, while warm fall/winter can reduce vernalization and extreme cold spring can cause freeze injury (Holman et al., 2011). Corn (rainfed) and rice show reduced yields at high precipitation (> 120 mm month^{-1}), this could be caused by the reduced incoming solar radiation due to more cloudiness or extreme weather conditions (e.g. hurricane/ tropical storms, floods) (Rosenzweig et al., 2002).

The negative impacts of excess precipitation on crop yields is worth noting. The reduction of crop yields is most significant in fine-textured soils for corn and wheat and in medium-textured soils for soybean. This is mostly likely due to the small saturated hydraulic conductivity of fine- and medium- textured soils. Corn, wheat and soybean production in fine-textured soils and along the Mississippi River can be negatively affected, particularly in states without intensive drainage infrastructure (e.g. states other than Iowa, Illinois, Indiana, and Ohio) or under poor drainage management. The wet stress effect on crop yields has been reported elsewhere. For example, based on simulations from a field-scale hydrological model that estimates crop yield reduction from water stress (Skaggs, 1978), Ale et al. (2009) found that wet stress in silty clay loams due to reduced drainage could lead to 1.3% of yield reduction on average out of 12 cropping seasons replicated 4 times at the Purdue University Water Quality Field Station. Similarly, Faé et al. (2020) found that saturated hydraulic conductivity was positively correlated to soybean yield collected over 22 site-years within medium- and fine-textured soils. These studies suggest that soil drainage as affected by soil texture should be considered in future modeling and management practices.

4.2. Soil texture effect on crop-temperature responses

Crops in medium- and fine- textured soils are less sensitive to temperature compared to coarse-textured soils (Fig. 5). This is also due to the higher available water capacity of medium- and fine- textured soils that can support more sufficient water supplies to crops during the growing seasons, particularly under water stress conditions. This water can enhance removal of latent heat via evapotranspiration from the soil and crop canopy and reduce the heat stress induced impacts on yield loss (e.g. closure of stomatal cells due to water deficit) (Long and Ort, 2010; Sacks and Kucharik, 2011; Jha et al., 2014). Because coarse-textured soils are susceptible to water depletion, rainfed crops in these soils have a higher dependence on temperature. The soil texture dependent effect on heat stress was observed in the meta-regression analysis of corn-based experiments by Steward et al. (2018) who found soil clay content could modify the interaction of heat and moisture stress. This was also consistent with the wheat-based growth chamber experiment by Rezaei et al. (2018) who found that yield reduced significantly by 24% grown on sandy soil substrate with increasing air temperature at anthesis at a sum of 12,000 °C min above 31 °C but not on loamy soils or soils consisting of peat and clay with high soil water holding capacity.

The effect of soil texture on crop-temperature interactions varies with crop type. Corn has a slightly higher optimal maximum growing season temperature than other crops in medium and fine textured soils. This can be also attributed to the fact that corn is a C4 plant while others are C3 plants. It is also noted that yields of winter wheat, barley and oats in coarse-textured soils are sensitive to temperature increases under cold conditions (minimum temperature: 0–5 °C, Appendix Fig. 3). This may be caused by the thermal conductivity of soils across different textures.

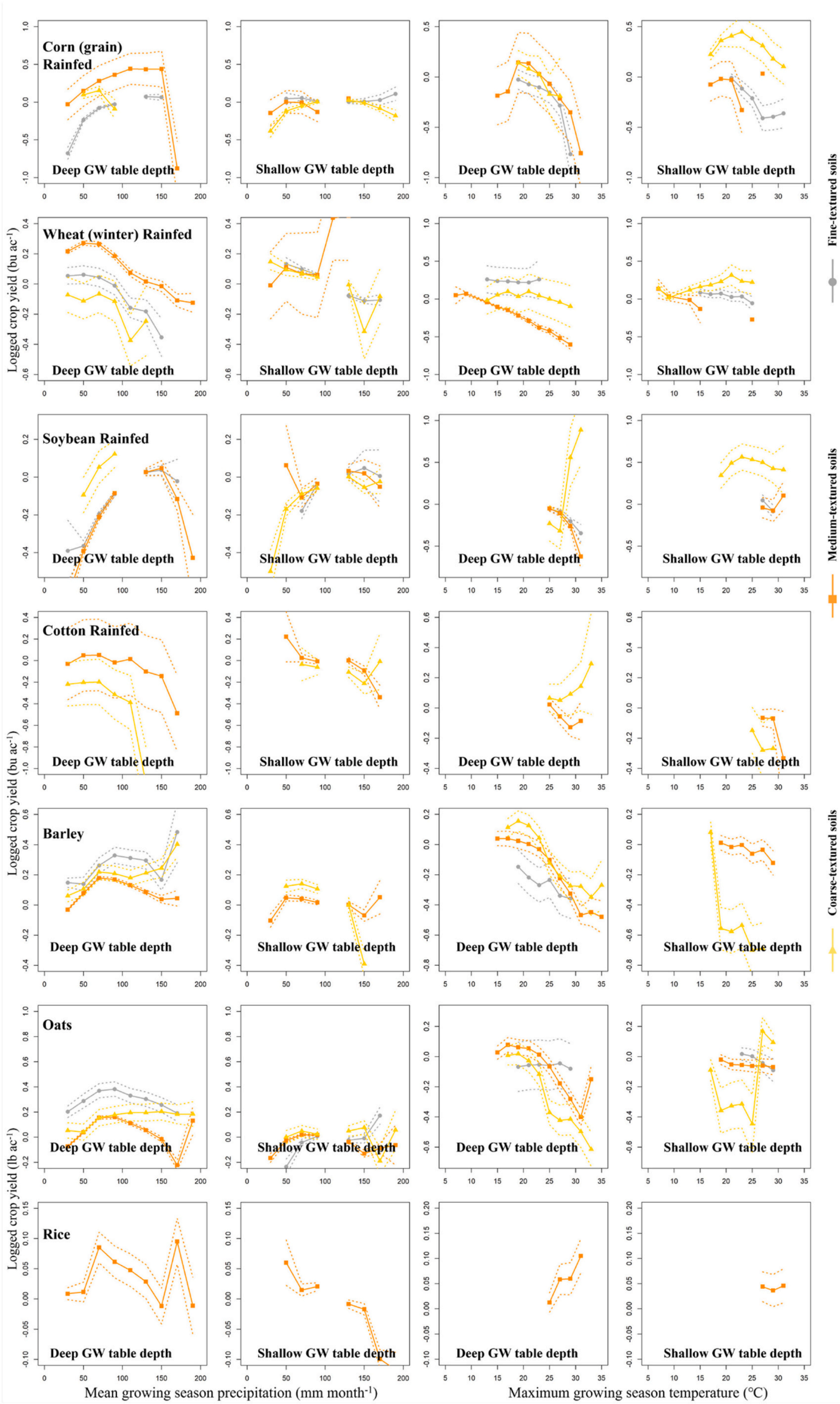

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Fig. 6. Soil-dependent crop yield responses to mean growing season precipitation (binned by 20 mm month^{-1}) and maximum growing season temperature (binned by 2 °C) across different soil texture classes (fine, medium, and coarse) with high (> 3 m) and low (< 3 m) groundwater (GW) table depth. Note: corn (grain), winter wheat, soybean and cotton were from rainfed (non-irrigated) fields. The solid and dashed lines represent the estimated coefficients and ± standard errors of the fixed effects (precipitation and maximum temperature) on crop yields, respectively.

In general, coarse-textured soils have high thermal conductivity (1.6–2.4 W m^{-1} K^{-1}) than medium-textured (1.4–1.6 W m^{-1} K^{-1}) and fine-textured (1.0–1.2 W m^{-1} K^{-1}) soils because the physical contacts of the particles are closer in coarse-textured soils (less pore space) (Bertermann et al., 2018). As such, coarse-textured soils often warm up more quickly and cools down more quickly than finer-texture soils. Early-warmed coarse-textured soils potentially enable early planting and germination in spring, which explains the increasing yields of winter wheat, barley, and oats under cold conditions. Early-frozen coarse-textured soils can lead to enhanced vernalization in winter, which may also explain the stronger dependence of winter wheat yield on minimum growing season temperature under cold conditions in coarse-textured soils (Appendix Fig. 3).

4.3. SOC effect on crop-climate responses

The decreased sensitivity (slope of yield-precipitation curves) of crop yields (e.g. corn, cotton, barley) to precipitation fluctuations with increasing SOC (SOC buffering effect, Fig. 4) can be attributed to the effect of SOC on water retention (Table 1). Increasing SOC concentration increases the porosity and water retention (field capacity, permanent wilting point, and available water content) of soils across all textures (Rawls et al., 2003). Soils with high SOC can provide more plant available water to maintain high yields via evapotranspiration during the water stress condition. This has been confirmed in field experiments for winter wheat (Barzegar et al., 2002) and canola (Abdullah, 2014), as well as county-level empirical analysis for corn (Williams et al., 2016). Similarly, soils with high SOC are more resistant to the impacts of high temperature on crop yields, most likely due to the increasing evapotranspiration with an increased soil water retention and as demonstrated in the empirical analysis for corn across four US states (Williams et al., 2016).

4.4. Soil texture and SOC effects on crop-climate responses under different groundwater table depths

The effects of groundwater table depth on crop phenology and root growth responses to climate variability have been recently included in crop growth models and reported in field-scale observations by Soylu et al. (2014, 2017). Similarly, the groundwater dependent plant root depth dynamics in response to precipitation and soil available water, termed as the root zone storage capacity have been studied and modeled at the global scale using remote sensing data (Wang-Erlandsson et al., 2016). Our empirical analysis confirms the groundwater table depth dependent crop-climate interactions exist at the national scale across the continental US and for all crop types except for rice (Fig. 6). The insensitive crop yield responses to precipitation and temperature changes in all texture and SOC classes with a shallow groundwater table are most likely due to the presence of an increased water supply via capillary movement for root uptake. However, when precipitation is extremely high (> 150 mm month^{-1}), crop yields are both low in soils with shallow and deep water table depths, possibly caused by flooding events and reduced incoming solar radiation.

4.5. Implications for sustainable agricultural production across the US and globe

These empirical results have a number of potential implications for designing soil management practices and sustainable agricultural production under a changing climate. First, crop responses to precipitation and temperature changes are a function of soil texture. As soil texture is relatively stable and difficult to change, the soil-texture dependent empirical response curves indicate that northern and central US counties with medium- and fine- textured soils (Fig. 3) are less sensitive to precipitation and temperature fluctuations whereas the states with coarse-textured soils (e.g. eastern coasts, southern borders, Nebraska, Great Lakes) are more likely to be affected by precipitation and temperature change (warming). Considering the projections of drought events in the large arid/semi regions across the western and southern US (Trenberth et al., 2014; Kuwayama et al., 2018; Peña-Gallardo et al., 2018; NIDIS, 2020), decreasing precipitation and increasing temperature over the next few decades could lead to potential yield decreases in these regions (e.g. Texas). However, warming in the northern US (e.g. Nebraska and Great Lakes) may increase the crop yields in these regions with coarse-textured soils. This has been previously suggested by Kucharik and Serbin (2008) and Deryng et al. (2014), and can be partially attributed to longer growing seasons that support the adaptation of higher-yielding crop varieties.

Second, the dependence of yield responses on SOC should be further studied and carefully considered in identifying improved agricultural management practices. Based on our empirical analysis, higher SOC amounts increase the resistance of row crops and yields to precipitation decreases and increasing temperatures, particularly for coarse-textured soils (Figs. 4 and 5). In water scarce regions such as the western US, increasing soil water retention by increasing SOC (e.g. adding biochar, a mixture of aromatic carbon, labile organic carbon, and inorganic carbon, Fidel et al., 2017) has the potential to increase crop yields or reduce yield losses in extremely hot and dry years (Williams et al., 2016), and can also support reduced irrigation water use (Kammann et al., 2011). However, the increase of soil water retention due to increasing SOC may reduce crop yields in wet regions where soils can be consistently saturated or have a high water table, particularly in poorly drained regions, such as the corn, wheat and soybean production areas in Great Lakes region (see Figs. 1–3). In regions with well-managed drainage infrastructure (e.g. tile drain systems in Iowa, Illinois, Indiana, and Ohio), the adverse impacts of excess precipitation on crop yields may be somewhat mitigated (refer to Fig. 4 and Ghane et al., 2012). However, increased soil moisture and retention could cause yield reduction in poorly drained soils in other wet regions of the US. In terms of temperature change, increasing SOC improves the resistance of crops to heat stress by supporting an increased likelihood of more root zone soil moisture to support increased transpiration necessary to keep leaves cooler and support photosynthesis. This is beneficial to producers in warm regions of the US where temperature increases lead to adverse impacts on crop yields (Figs. 2 and 5). However, increasing SOC could cause soils to warm and dry more slowly in spring, delaying planting and seed germination. Future research is needed to evaluate the magnitude of the overall effects of SOC on water storage and energy conservation for different crop types, soil textures, and climate regions.

Third, irrigation and the depth to groundwater are also important in understanding crop-climate responses. As our results show, irrigation is an effective management practice to increase crop resilience to a changing climate. This was also reported by others (e.g. Holman et al., 2011; Kucharik et al., 2020). From a sustainable agricultural management perspective, research is needed to evaluate the effectiveness of irrigation practices on crop production and within the concept of "water-food-energy nexus" across different climate regimes, soil textures, and under different climate change scenarios (Nocco et al., 2019; Sacks and Kucharik, 2011). In this study, the long-term depth to groundwater table was used and was shown to have important feedbacks

Table 2
Summary statistics of key hydraulic and thermal properties of soils in major texture classes in the US. Note: SOC, soil organic carbon concentration. Note: * refer to values that were inferred based on previous studies.

Soil texture	Example	SOC	Porosity	Field capacity	Permanent witling point	Available water capacity	Saturated hydraulic conductivity (cm day^{-1})	Thermal conductivity (W m^{-1} K^{-1})	References
Fine-textured	Silty loam & Silty clay loam	High*	0.25–0.60	0.60–0.70	0.26–0.35	0.30–0.35	–	–	Swiss Standard SN 670 010b, n.d., Lang (1878), Ulrich (1894), Kersten (1949),(Jamison and Kroth, 1958) Bowers and Hanks (1962), Hough (1969), Clapp and Hornberger (1978), Ghuman and Lal (1985), Carsel and Parrish (1988), (Bauer and Black, 1992) Miller and White (1998); (Peters-Lidard et al., 1998) Abu-Hamdeh and Reeder (2000), Moskal et al. (2001), Schaap et al. (2001), Bortoluzzi (2003), Rawls et al. (2003), Bruand et al. (2005), Lesturgez (2005), (Côté and Konrad, 2005) Das, 2008; Olness and Archer, 2005, Dexter et al. (2008), Bertermann et al. (2018), Libohova et al. (2018), Yost and Hartemink (2019)
		Low	0.21–0.56	0.48–0.49	0.20–0.26	0.20–0.25	11–18	1.0–1.2	
Medium-textured	Loam & Clay loam	High*	0.30–0.50	0.55–0.60	0.20–0.25	0.35–0.40	–	–	
		Low	0.29–0.41	0.45–0.48	0.15–0.20	0.25–0.30	8–12	1.4–1.6	
Coarse-textured	Sandy loam, Sandy clay loam, Loamy sand, & Sand	High*	0.35–0.60	0.35–0.55	0.20–0.40	0.10–0.15	–	–	
		Low	0.26–0.46	0.20–0.40	0.07–0.18	0.08–0.13	13–640	1.6–2.4	
Others	Sandy clay & Clay	High*	0.50–0.75	0.55	0.25	0.30	–	–	
		Low	0.39–0.59	0.48	0.29	0.21	11–14	1.0–2.0	

on crop production. It would be worth further investigating the dynamics of groundwater table and crop phenology (e.g. root density and dynamics) and their interactions in response to climate variations. In particular, ecosystem models that are used to study these interactions need further improvement to fully account for the coupling between groundwater and plant growth as well as simulation of the complete water balance in agroecosystems (Zipper et al., 2017).

Last, the crop-climate responses derived from nationwide crop yields data can be applied to understand yield responses in different climate regimes. In this analysis, the interactions between precipitation and temperature were separated into different climate regimes for rainfed corn, winter wheat, soybean and cotton (shown in Appendix Figs. 10 and 11). The effects of soil texture and SOC were still valid in each of the climate regimes (i.e. warm + wet, warm + dry, cold + wet, cold + dry). However, the limited magnitude of precipitation and temperature may smooth the effects of soil properties on crop–climate interactions. This suggests that location-specific management practices should be carefully designed to account for the climate-specific crop responses for food production.

4.6. Future work

First, field observations, empirical studies and mechanistic modeling (e.g. Kucharik, 2003; Robinson et al., 2019) could be conducted to further evaluate the effects of climate change and soil management practices on soil texture and SOC stocks and their interactions with crop yields. Although studies have revealed the importance of soil structure and soil aggregate stability (Kravchenko et al., 2019) and carbon stocks (Kucharik et al., 2001; Luo et al., 2020; Osanai et al., 2020) on terrestrial carbon, nitrogen, and water cycles, it remains unknown how soil texture and SOC would interact with other factors such as climate, groundwater, and agricultural management (e.g. fertilization, irrigation) on crop yields. In addition, future work can be conducted using historical climate data to understand the impacts of changing climate patterns on crop yields and identify regions that are more susceptible to climate variability due to their differences in soil texture, SOC, and depth to groundwater table.

Second, the crop–climate interactions identified in this study need to be further studied across the world. As shown in our empirical models, crop yields increased from 1958 to 2019 in the US (refer to the fixed effect representing Year, see Method section), due to the increasing irrigation and fertilization, better crop varieties (e.g. plant breeding and biotechnology), and adoption of best management practices (Kucharik, 2006; Sharpley et al., 2006; Kucharik, 2008; Lu et al., 2018; Kucharik et al., 2020; USDA, 2020a, 2020b). Although the patterns identified in the US may be similar in certain regions (e.g. Australia, Brazil, China, Europe) as reported by Hsiang et al. (2013), further research is needed, particularly in different climate regimes, to further study the interactions between climate (e.g. precipitation and temperature) on crop yields and better under how limitations to irrigation water and plant nutrient conditions (e.g. fertilizers) can affect the soil-dependent crop-climate response.

5. Conclusions

We investigated the effects of soil texture and soil organic carbon concentration (SOC) on the yield responses of seven major crops (corn, winter wheat, soybean, cotton, barley, oats, rice) to growing season precipitation and temperature between 1958 and 2019 across the conterminous US and evaluate the effects of irrigation and groundwater depth on crop-climate responses.

- Crop yields are most sensitive and most negatively impacted by precipitation decreases and temperature increases in coarse-textured soils and are somewhat less responsive to these drivers in medium- and fine- textured soils.

- Increasing SOC concentration (> 2%) supports reduced crop sensitivity to decreasing precipitation and increasing temperatures
- Irrigation and the presence of a shallow groundwater table (< 3 m) increase the resilience of crops to reduced precipitation and increasing temperatures, with the effects being dependent on soil texture and SOC.
- To enhance food security for a rapidly growing global population under a changing climate, best management practices should be adopted that improve soil structure and carbon stocks that can increase water storage ("Green Water") and nutrient retention and energy conservation.
- The spatial-temporal variations soil texture, SOC, and depth to water table and their effects on yield response to climate variability should be properly accounted for in agroecosystem modeling studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103085.

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