


## PRIMARY RESEARCH ARTICLE

# Soil organic carbon in irrigated agricultural systems: A meta-analysis

David Emde<sup>1</sup>  | Kirsten D. Hannam<sup>2</sup> | Ilka Most<sup>1</sup> | Louise M. Nelson<sup>1</sup> | Melanie D. Jones<sup>1</sup>

<sup>1</sup>Biology Department, The University of British Columbia Okanagan, Kelowna, BC, Canada

<sup>2</sup>Agriculture and Agri-Food Canada, Summerland Research and Development Centre, Summerland, BC, Canada

**Correspondence**

David Emde, Biology Department, The University of British Columbia Okanagan, Kelowna, BC, Canada.  
Email: dsemde@gmail.com

**Funding information**

Agriculture and Agri-food Canada

**Abstract**

Over the last 200 years, conversion of non-cultivated land for agriculture has substantially reduced global soil organic carbon (SOC) stocks in upper soil layers. Nevertheless, practices such as no- or reduced tillage, application of organic soil amendments, and maintenance of continuous cover can increase SOC in agricultural fields. While these management practices have been well studied, the effects on SOC of cropping systems that incorporate irrigation are poorly understood. Given the large, and expanding, agricultural landbase under irrigation across the globe, this is a critical knowledge gap for climate change mitigation. We undertook a systematic literature review and subsequent meta-analysis of data from studies that examined changes in SOC on irrigated agricultural sites through time. We investigated changes in SOC by climate (aridity), soil texture, and irrigation method with the following objectives: (i) to examine the impact of irrigated agriculture on SOC storage; and (ii) to identify the conditions under which irrigated agriculture is most likely to enhance SOC. Overall, irrigated agriculture increased SOC stocks by 5.9%, with little effect of study length (2–47 years). However, changes in SOC varied by climate and soil depth, with the greatest increase in SOC observed on irrigated semi-arid sites at the 0–10 cm depth (14.8%). Additionally, SOC increased in irrigated fine- and medium-textured soils but not coarse-textured soils. Furthermore, while there was no overall change to SOC in flood/furrow irrigated sites, SOC tended to increase in sprinkler irrigated sites, and decrease in drip irrigated sites, especially at depths below 10 cm. This work sheds light on the nuances of SOC change across irrigated agricultural systems, highlights the importance of studying SOC storage in deeper soils, and will help guide future research on the impacts of irrigated agriculture on SOC.

**KEYWORDS**

agriculture, aridity, climate, irrigation, soil depth, soil organic carbon, soil texture

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2021 The Authors. *Global Change Biology* published by John Wiley & Sons Ltd.

## 1 | INTRODUCTION

Irrigated agricultural land amounts to 275 million ha worldwide and accounts for 40% of global food production (The United Nations World Water Development, 2014). As consumption per capita increases and greater demand is put on agricultural resources, irrigated agriculture is projected to increase by an average of 1.65 million ha per year until 2030 (The United Nations World Water Development, 2014). By enhancing agricultural productivity per unit area of land, particularly in arid and semi-arid climates, irrigation may also help mitigate greenhouse gas emissions by reducing the rate at which unmanaged systems under native vegetation are converted to agronomic systems, thereby preventing the massive losses of soil organic carbon (SOC) often associated with land conversion (McGill et al., 2018; Poeplau et al., 2011; Wei et al., 2014; Wiesmeier et al., 2019). SOC and the organic matter in which it is bound are integral to maintaining key soil functions in agricultural soils, for example, water and nutrient retention, soil microbial activity, and maintenance of a healthy physicochemical balance (Trost et al., 2013). These functions, in turn, help maintain agricultural productivity, which is crucial for keeping up with the growing demand for food (Wiesmeier et al., 2016). Irrigation has the potential to affect SOC dynamics in agricultural soils not only by changing soil moisture dynamics and crop productivity but also by translocating soluble material through the soil profile, by transporting material across the soil surface, and by modifying the metabolic behaviour of microbial communities (Minasny et al., 2017; Tautges et al., 2019; Trost et al., 2013; Xu et al., 2016).

There are three broad types of study that can be used to examine changes in SOC storage under irrigated agriculture: (i) studies that compare SOC in irrigated and rainfed plots; (ii) studies that compare SOC in unmanaged 'natural' and irrigated plots; and (iii) studies that compare SOC in irrigated plots at the beginning and end of an experiment. Studies that compare SOC in irrigated and rainfed field plots present the most obvious opportunity for studying the effects of irrigation on SOC, but such experiments can only be conducted in sufficiently humid regions, where crop production is possible (albeit less successful) without supplementary irrigation. Given that irrigation is needed most in arid/semi-arid regions that do not receive sufficient natural precipitation to support commercial agriculture, comparisons of SOC in irrigated and rainfed plots cannot capture the effects of irrigated agriculture in the regions where irrigation is most widely applied. Furthermore, comparisons of SOC in irrigated and rainfed plot are often confounded by differences in crop type or planting density. Similarly, studies that compare SOC under 'natural', or 'unmanaged' vegetation and adjacent irrigated fields are also confounded by differences in plant species (i.e. agronomic vs. native species), and by the effect of land-use conversion, which often causes dramatic losses in SOC (Don et al., 2011; Guo & Gifford, 2002; Ogle et al., 2005; Rusinamhodzi et al., 2011). Consequently, we chose to focus our analysis on studies that compared SOC in the same irrigated plots or fields at the beginning and end of an experiment.

The requirement for irrigation is highest in climatic regions where low natural rainfall limits crop productivity. In a recent

literature review, Trost et al., (2013) calculated that irrigation in regions with a semi-arid climate increased SOC by 11%–35% relative to that under native vegetation, and suggested that this effect was heavily influenced by initial SOC levels and was strongest in surface soils. However, a recent soil survey of the western Mediterranean basin near the Spanish–Portuguese border revealed that SOC storage tends to be greater in irrigated Fluvisols, Luvisols, and Calcisols than in equivalent rainfed soils but similar in irrigated and rainfed Cambisols (Telo da Gama et al., 2019).

The effect of irrigation on SOC accumulation in more mesic climatic regions is even less well defined. In a long-term study at the Kellogg Biological Station in Michigan, USA McGill et al., (2018) found that SOC increased in irrigated corn fields relative to rainfed controls at a rate of 1% year<sup>-1</sup> for 12 years. By contrast, studies in Brandenburg Country, Germany by Ellmer and Baumecher (2002), and Vienna, Austria by Dersch and Böhm (2001) found no changes in SOC with irrigation of cereal crops in studies ranging from 21 to 65 years. Rotenberg et al., (2005) reported that irrigation of vegetable crops at the University of Wisconsin's Hancock Agricultural Research Station caused SOC stocks to decline by over 18%. Moreover, irrigation of temperate pastureland in New Zealand caused SOC to decrease at depth, with losses substantial enough to negate any increases in SOC near the soil surface (Condrón et al., 2014). Thus, there is no current consensus on whether the overall effect of irrigation on SOC stocks is positive, neutral, or negative; and how it varies with climate zone.

As global efforts to reduce greenhouse gas emissions intensify, it is more important than ever to investigate the potential for agriculture to promote soil carbon sequestration. The degree to which SOC is increased, and the relative influence of irrigation compared with other confounding agricultural practices on the same site is not well documented (Condrón et al., 2014; Wiesmeier et al., 2019). The few studies that have attempted to quantify the effects of irrigation on SOC have highlighted the difficulty in isolating the effects of irrigation per se on SOC from the effects of other agricultural management practices; as such, many studies have focussed on simple agricultural systems with few other inputs, such as pastures. Alternatively, many studies have compared the effects of irrigation with freshwater and wastewater on soil properties (Andrews et al., 2016; Häring et al., 2017; Ramirez-Fuentes et al., 2002). To improve our understanding of the impact on SOC of irrigation with freshwater, we undertook a meta-analysis of the global literature to (i) summarize and characterize changes in SOC in irrigated agriculture; and (ii) identify the conditions under which irrigated agriculture is most likely to enhance SOC.

## 2 | METHODS

### 2.1 | Study selection

Each of the studies included in our analysis was an agricultural experiment that included irrigation with freshwater as part of plot management, held management practices consistent throughout

the trial, and measured SOC at least twice during the study. The use of irrigation was the unifying theme for selecting studies to include in our analysis. However, a variety of other management practices were also applied in each study, including tillage, crop rotation, manure and fertilizer application, etc.; selected study sites were also planted to a range of crop types and were irrigated using diverse methods. Thus, we determined that it was not possible to isolate the effect of irrigation per se on SOC stock using our approach. Instead, our aim was to characterize trends in SOC under 'irrigated agriculture', which includes a suite of diverse management practices. To that end, peer-reviewed research papers were selected from Web of Science and Google Scholar using the following search string:

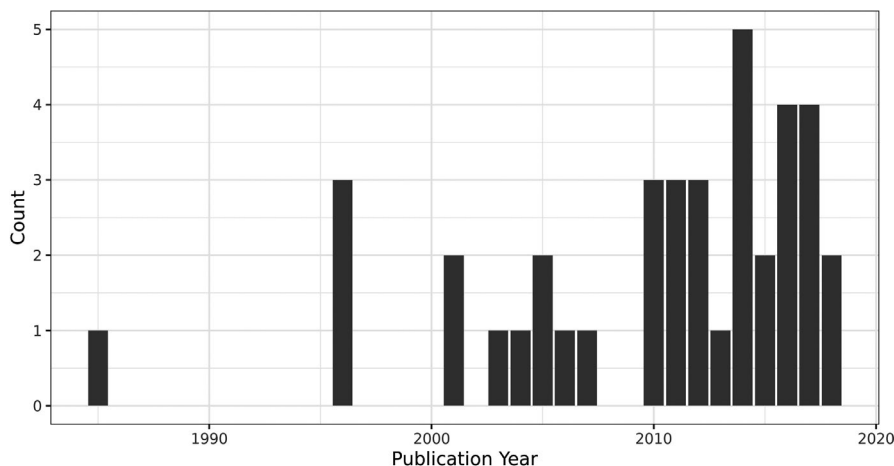
```
agric* AND irrigat* AND (("soil carbon" OR (soil AND "inorganic carbon")) OR "soil nitrogen" OR "soil pH") NOT (rice OR tropic* OR forest*) OR (agricultur* OR farm*) AND (irrigat*) AND (soil NEAR/2 (carbon OR nitrogen))
```

Research papers were then systematically assessed to determine their suitability for inclusion in the meta-analysis using a set of predefined criteria (Supporting Information S1). Only data from field studies were included (i.e. no greenhouse or laboratory studies).

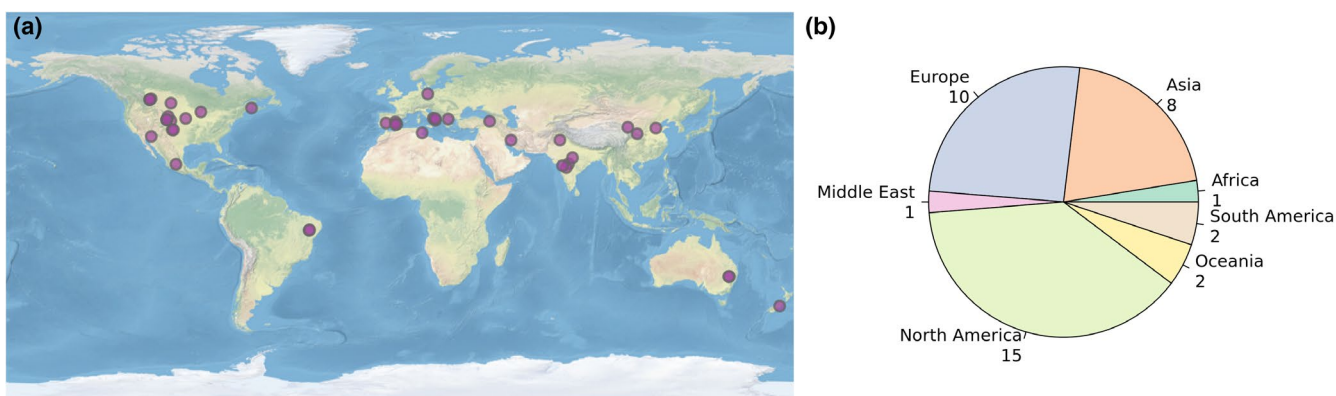
Also excluded were (i) data from experiments conducted in rice paddies or forests; (ii) papers that provided insufficient detail about study design; (iii) papers that included only one growing season; and (iv) papers that used irrigation water sources other than fresh water. The final literature search was completed on 14 January 2019, and included studies published from January 1985 to July 2018, with 68.6% published after 2010 (Figure 1). Although our initial intention was to characterize changes in SOC, soil inorganic C (SIC) and total soil N associated with irrigated agriculture (Supporting Information S1), we found few relevant SIC and total soil N data; as a consequence, we chose to focus our meta-analysis on SOC only. Manual screening of papers that passed these filters resulted in 35 eligible studies, covering 42 study sites, and including 297 observations; 38.5% of the study sites were located in North America, 20.5% in Asia, 25.6% in Europe, 2.6% each in the Middle East and Africa, and 5.1% each in South America and Oceania (Figure 2).

## 2.2 | Data collection

We compiled SOC data from all papers that met the selection criteria described above. Soil organic C data collected at the time of treatment establishment (i.e. 'time 1') were considered data from



**FIGURE 1** Count of publications included in meta-analysis dataset by year of publication



**FIGURE 2** (a) Spatial distribution of study sites included in the meta-analysis, including 297 observations from 42 study sites. (b) Breakdown of study sites included in meta-analysis dataset, by geographical area

the control treatment and SOC data collected at least 1 year after the study was established (i.e. 'time 2') were considered data from the 'experimental' treatment. If multiple years of post-treatment SOC data were reported, data were taken from the final year of the study only, to avoid pseudo-replication.

Most papers reported SOC data as either C concentration (i.e. SOC kg<sup>-1</sup> dry soil) or C stock (Mg SOC ha<sup>-1</sup>). Given that changes in SOC stock most accurately reflect changes in soil carbon storage, SOC concentration data were converted to SOC stocks, when necessary, using the following equation:

$$\text{SOC}_{\text{stock}} (\text{Mg C ha}^{-1}) = \text{SOC}_{\text{conc.}} \times \text{BD} \times t \times 0.1, \quad (1)$$

where SOC<sub>conc.</sub> is soil the organic carbon concentration in g kg<sup>-1</sup>, BD is the bulk density in g cm<sup>-3</sup>, *t* is the thickness of the depth increment (cm), and 0.1 is the conversion factor for Mg ha<sup>-1</sup>. Despite its importance for determination of soil properties and SOC stock, BD was reported in only 43% of the included studies. We used a random forest (RF) algorithm to estimate the missing bulk density values for each soil depth category, using all available predictor variables, in a manner analogous to a pedotransfer function (Supporting Information S2; Akpa et al., 2016; Chen et al., 2018; Sequeira et al., 2014). RF works by combining a large number of regression trees, trained using bootstrap aggregation, to build a robust predictive model that is resistant to noise in the data (Breiman, 2001). The R code for this RF model is available at <https://github.com/dsemde/Emde-et-al.2021-public>.

When data were presented in figures, rather than tables, values were estimated using WebPlotDigitizer (<https://apps.automeris.io/wpd/>). Standard deviation (SD) and number of replicates (*n*) were also recorded. Only 30% of the papers reported SD or standard error (SE). Where SE was reported, the SD was calculated as

$$\text{SD} = \text{SE} \times \sqrt{n}, \quad (2)$$

where SE is the standard error and *n* is the number of observations. If no SD or SE was reported, the SD was estimated using the mean coefficient of variation (Jerabkova et al., 2011).

Categorical and continuous meta-data that could be used as possible predictors of irrigation-related changes in SOC were also collected from each study (Table 1). When key meta-data were not provided, they were estimated, where possible. Missing elevation data were filled in using longitude and latitude values reported in the paper and the rasterized ETOPO1 Global Relief Model (Fick & Hijmans, 2017). Average temperature and precipitation data were typically reported for the specific study period; however, there were cases where a standard 30-year average was reported instead. In light of this, longitude and latitude data were again used to extract 30-year averages from global rasters from worldclim.org for all sites, to both standardize the existing values and fill in those that were missing.

Soil depth measurements varied between studies. To standardize comparisons among studies, data were placed in soil depth categories based on the most common sample depths across all studies: 0–10, 10–20, 20–30, and 30+ cm. Data from studies that sampled soils outside of these ranges were standardized, as described in Angers and Eriksen-Hamel (2008). That is, values were fitted to a specific depth category by first finding the median of the reported depth increment, and then determining the depth category into which the median value fell. Where studies reported more than one SOC measurement in one depth category, a single value was calculated, using a weighted average.

Given that climate is a strong determinant of irrigation requirements and the impact of irrigation on SOC (Troost et al., 2013), we believed it was important to identify climate zones both accurately and consistently across sites. Therefore, a rasterized GeoTIFF containing global aridity index values was used along with climate delineations outlined in Trabucco and Zomer (2018) to determine the aridity index and a more fine-grained aridity category for each study

**TABLE 1** Summary of variables collected from included studies, with the three main analysis categories shown in bold. Data in parentheses indicate the percentage of study sites that reported each variable

Site details	Agricultural details	Irrigation details	Sample collection
Geographical location (100)	Crop type (100)	Years since irrigation (100) <sup>a</sup>	Study scale (100)
Elevation (59.2)	Multiple crops/rotation (100)	<b>Irrigation method (92.1)</b>	Sample depth (100) <sup>a</sup>
Avg. annual precip. (76.3)	Tillage frequency (68.4)	Irrigation water source (98.7)	Soil bulk density (43.0) <sup>a</sup>
Avg. annual temp. (39.5)	Tillage type (78.9)	Irrigation water pH (9.2)	<b>Soil texture (% sand/clay) (97.4)<sup>a</sup></b>
Climate (80.3)	Crop residue removal (77.6)	Irrigation water HCO <sub>3</sub> (2.6)	Soil pH (52.6) <sup>a</sup>
<b>Aridity index (100)<sup>b</sup></b>	Grazing status (88.2)	Irrigation water calcium (3.9)	Number of samples ( <i>n</i> ) (100) <sup>a</sup>
	Use of cover crops (96.0)	Irrigation water Organic C (0)	Organic C (incl. SD) (30.0) <sup>a</sup>
	Inorganic N application (90.8)	Irrigation water N (2.6)	
	Herbicide use (65.8)		
	Organic matter application (92.1)		
	Inorganic C application (90.8)		

<sup>a</sup>Data were collected separately for the control and experimental treatments.

<sup>b</sup>Aridity Index was collected from a rasterized GeoTIFF using reported longitude and latitude values.

location. Aridity index was calculated as the ratio of precipitation to potential evapotranspiration according to the following equation:

$$\text{Aridity Index} = \frac{\text{Mean annual precipitation}}{\text{Mean annual reference evapo-transpiration}}. \quad (3)$$

Aridity index categories: arid (0.03–0.2), semi-arid (0.2–0.5), dry sub-humid (0.5–0.65), and humid (>0.65; Trabucco & Zomer, 2018).

Other categorical variables were designated using similar approaches to those in previous meta-analyses. For example, crop information was converted from the originally reported crop species to one of three categories indicating the dominant crop type for the study period, as outlined by Aguilera et al., (2013). These categories were as follows: cereals, including crop rotations in which cereals were the dominant crop; horticulture, including crop rotations in which vegetables were the dominant crop; and woody perennial crops, including orchards and vineyards (Supporting Information S3). Crop types were considered dominant if they accounted for the greatest portion of the crops in rotation, and present in the study plot for the greatest portion of the study period. Soil texture categories were grouped according to Jian et al., (2020) as coarse-, medium-, or fine-textured, based on USDA soil texture categories. Coarse-textured soils included sand, loamy sand, and sandy loam; medium-textured soils included sandy clay loam, loam, silt loam, and silt; and fine-textured soils included clay, sandy clay, clay loam, silty clay, and silty clay loam. Finally, study duration categories were determined as in Xu et al., (2019): short term ( $\leq 5$  years), medium term (6–15 years), and long term (>15 years).

### 2.3 | Publication bias

Publication bias was analysed using both funnel plots (including trim/fill methods; Halupka & Halupka, 2017; Viechtbauer, 2010) and Rosenberg's failsafe N (Rosenberg, 2005). Using these measurements, the likelihood of publication bias was assessed as non-problematic (Supporting Information S4 and S5) and is not discussed further.

### 2.4 | Meta-analysis

In meta-analysis, either a fixed effect or random-effect model can be generated. If the dataset is sufficiently large and there is very small inter-study heterogeneity, a fixed effect model may be used (Bashir & Conlon, 2018; Field & Gillett, 2010). However, our meta-analysis consisted of studies from around the world, including sites with a broad range of SOC contents and soil characteristics; we therefore adopted a random-effect approach.

We used natural logarithmic response ratios to calculate the relative effect sizes of various management practices, environmental factors, and physicochemical characteristics over time in 'experimental' (time 2, as described above) plots relative to 'controls' (time 1, as described above). This metric allowed us to compare the

proportional change in SOC across studies in our global dataset (Gurevitch et al., 2018; Hedges et al., 1999). Response ratios were calculated as:

$$RR_{\text{TIME 1 vs TIME 2}} = \left( \frac{\text{SOC}_{\text{TIME 2}}}{\text{SOC}_{\text{TIME 1}}} \right), \quad (4)$$

where  $\text{SOC}_{\text{TIME 1}}$  is the soil organic carbon stock at 'time 1' and  $\text{SOC}_{\text{TIME 2}}$  is the soil organic carbon stock at 'time 2'. To interpret effect size more easily, response ratios were further transformed into percent SOC stock change:

$$\Delta\text{SOC}_{\text{stock}}(\%) = (e^{\text{RR}_{\text{TIME 1 vs TIME 2}}} - 1) \times 100, \quad (5)$$

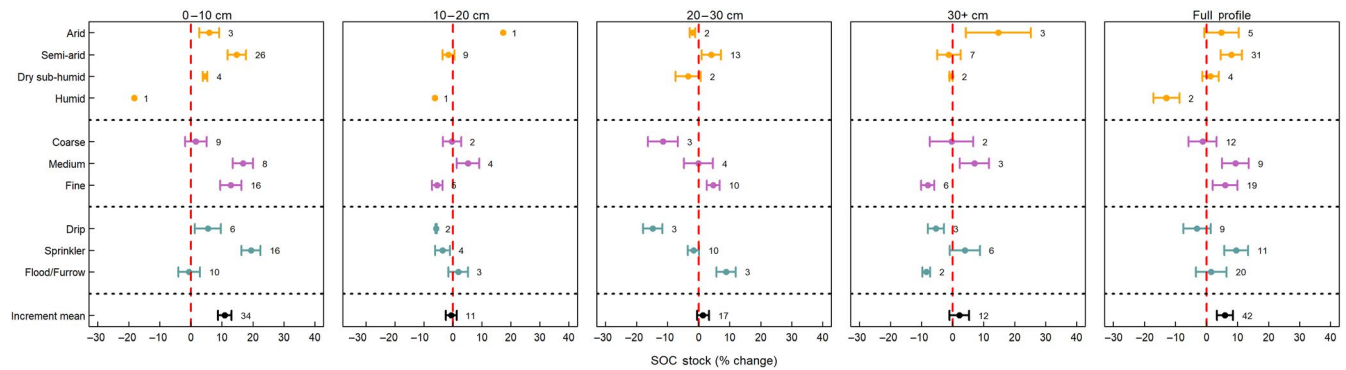
where  $\text{RR}_{\text{TIME 1 vs TIME 2}}$  is the log-transformed response ratio used to compare the change in SOC stock between 'time 1' and 'time 2' as described in Equation (4). According to this equation, negative  $\Delta\text{SOC}_{\text{stock}}$  values indicate a loss of SOC stock over time, positive values indicate a gain in SOC stock over time, and values of '0' indicate no change between 'time 1' and at 'time 2'. That is to say, these analyses were used to assess the effect of irrigation on total carbon storage.

Soil organic carbon change rate was calculated using the values from Equation (5) in combination with each individual study duration as follows:

$$\text{SOC}_{\text{stock}} \text{ change rate}(\% \text{ year}^{-1}) = \frac{\Delta\text{SOC}_{\text{stock}}}{\text{study duration}}, \quad (6)$$

where  $\Delta\text{SOC}_{\text{stock}}$  and study duration (in years) differed on a per-study basis. To further examine the importance of study duration on changes in SOC storage in irrigated agriculture, we additionally placed each data point into one of three study duration categories: short ( $\leq 5$  years between initial [t1] SOC measurement and final [t2] SOC measurement), medium (6–15 years) and long (>15 years; Supporting Information S8).

Data analyses were conducted by soil sample depth category as well as for the full soil profile, because previous meta-analyses have shown that sample depth is a strong predictor of management-caused changes in soil carbon storage (Bai et al., 2019; Du et al., 2017). To explore the importance of soil properties, climatic factors, and management practices on changes in SOC stocks and SOC change rate, we used a combination of simple linear regression (for continuous explanatory variables) and ANOVA (for categorical explanatory variables) as appropriate. From these analyses, we selected a sub-set of variables that best explained changes in SOC (i.e. aridity class and irrigation method), or that warranted further exploration due to their well-documented importance in determining SOC storage (i.e. soil texture). The weighted means and SDs of this sub-set of explanatory variables were determined using the R package 'Weighted.Desc.Stats' (Parchami, 2016). These estimators and their 95% confidence intervals are reported in Figure 3. Treatment effects were considered significant if their 95% confidence interval did not cross 0.



**FIGURE 3** Change in soil organic carbon (SOC) stocks in irrigated agricultural systems by depth increment and climatic category, soil texture category, and irrigation method. Depth increments are indicated at the top of each panel. Filled circles with error bars represent the mean change in SOC and their respective 95% CI. Where 95% CI does not overlap 0% (indicated by a vertical red line), SOC has significantly changed over time. Data points may contain studies of varying duration; however, a majority of study durations were <5 years. The numbers to the right of each data point indicate the total number of observations that were used to calculate the mean

All analyses were carried out in R version 3.6.3 and 4.0.0 (R Core Team, 2020). The meta-analyses were conducted using the 'metafor' package (Viechtbauer, 2010). Simple linear regressions were carried out using the linear model function (*lm*), and ANOVA was carried out using the ANOVA function (*anova*) with Tukey's HSD (*TukeyHSD*) used as an a posteriori test.

### 3 | RESULTS

#### 3.1 | Overall changes by depth increment

Overall, irrigated agriculture increased SOC stocks by 5.9% (black data point in the Full Profile panel of Figure 3). Analyzed by depth increment, irrigated agriculture increased SOC by 10.9% at the 0-10 cm depth, but did not cause significant changes in SOC at the 10-20, 20-30, or 30+ cm depths.

#### 3.2 | Effects of climate, texture, and irrigation method

Based on our understanding of the drivers of SOC storage, several explanatory variables were initially considered for their possible importance in modifying the strength and direction of changes in SOC stocks caused by irrigated agriculture (Table 1). According to the criteria used to select variables included in the final analysis (Supporting Information S6), we found that aridity class, irrigation method, and soil texture were strong predictors of change in SOC in irrigated agricultural systems. The utility of study duration as a predictor of changes in SOC is discussed separately below. Average annual precipitation, average annual temperature, elevation, crop type, and other management practices had no or only minor importance and are not discussed further (Supporting Information S6).

##### 3.2.1 | Effects of aridity

In general, irrigated agriculture increased SOC stocks in drier climates (Figure 3). In arid regions, for example, mean SOC increased by 5.9% at the 0-10 cm depth; 17.2% at the 10-20 cm depth; and 14.8% at the 30+ cm depth (Figure 3). Changes in SOC at the 20-30 cm depth were not statistically significant. In semi-arid regions, SOC increased by 14.8% at the 0-10 cm depth and 4.1% at the 20-30 cm depth, with no statistically significant changes at other depths. In dry sub-humid regions, SOC increased by 4.6% at the 0-10 cm depth, and showed no statistically significant changes at the 20-30 cm and 30+ cm depths (there were no data available for the 10-20 cm depth). Irrigated agriculture in humid regions appeared to reduce SOC stocks at the 0-10 and 10-20 cm depths, but this is based on only two data points.

##### 3.2.2 | Effects of soil texture

Over the whole profile, irrigated agriculture increased SOC stocks in medium- and fine-textured soils but not in coarse-textured soils (Figure 3). However, results varied by depth (Figure 3). In coarse-textured soils, irrigated agriculture reduced SOC at the 20-30 cm depth (-11.5%) but had no significant effect at other soil depths. In medium-textured soils, irrigated agriculture increased SOC at the 0-10 cm (16.8%), 10-20 cm (5.2%) and 30+ cm (7.0%) depths but had no significant effect at the 20-30 cm depth. In fine-textured soils, irrigated agriculture increased SOC at the 0-10 cm depth (12.9%) and 20-30 cm (4.7%) depths, and reduced SOC at the 10-20 cm (-5.4%) and 30+ cm (-8.0%) depths.

##### 3.2.3 | Effects of irrigation method

Overall, SOC stocks increased significantly under sprinkler irrigation (9.5%) and showed no significant change in drip and flood/furrow

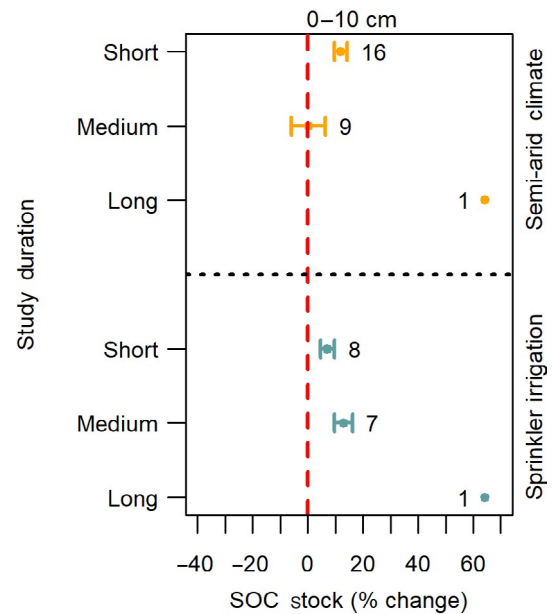
irrigated systems. The strength and direction of changes in SOC stocks also varied by irrigation method and soil depth (Figure 3). Drip irrigation increased SOC at the 0–10 cm depth (5.5%) but reduced SOC at the 10–20 cm (–5.9%), 20–30 cm (–14.8%), and 30+ cm (–5.3%) depths. By contrast, sprinkler irrigation increased SOC at the 0–10 cm depth (19.4%), reduced SOC at the 10–20 cm depth (–3.6%), and caused no change in deeper soils. Flood/furrow irrigation increased SOC at the 20–30 cm depth (8.9%), reduced SOC at the 30+ cm depth (–8.5%), and caused no change in shallower soils.

### 3.3 | Effects of study duration

Although the t1 data used in our study were collected at the beginning of the published experiments, there is always the possibility that previous agricultural practices, including irrigation, carried out on the plots prior to these experiments may have had carry-over effects. However, we investigated the past history of each experimental site to ensure that differences in SOC between the beginning and end of each experiment were not confounded by recent land-use change, for example, conversion from ‘non-agricultural’ or ‘unmanaged’ land (Supporting Information S7). Although site management history was not consistently well documented, most of the selected studies were carried out on well-established agricultural research sites (52.8%); several of the remaining studies were carried out on long-term commercially managed sites or on sites with otherwise less well-documented management histories. Only two studies (Sainju et al., 2014; Undersander & Ger, 1985) appear to have been conducted on land that had recently (2 and 3 years prior, respectively) been converted from a ‘natural’ system to an agricultural system. Therefore, we are confident that most studies included in this analysis had not recently undergone land-use conversion from ‘natural’ systems. If the start of a given experiment had coincided with the initiation of irrigation, however, then the change in SOC we observed might also be confounded by the effects of changes in management practices. However, our assessment of the study site descriptions from each publication suggests that most experimental plots had already been irrigated as part of previous management practices, that is, prior to ‘t1’. Therefore, overall, the changes in SOC we observed appear to be caused by the suite of practices associated with irrigated agriculture, rather than by recent changes in management or land use.

The treatment effects described above do not account for differences in study duration, that is, the fact that treatment effects may increase, decrease, or change direction with time. In many cases, there were too few studies to draw conclusions about the effect of study duration on treatment effects when separated by study and soil depth categories (Supporting Information S9–S11). Nevertheless, there were sufficient data to examine the effects of short- and medium-term study duration on changes in SOC at the 0–10 cm depth in (i) semi-arid climates; and (ii) under sprinkler irrigation (Figure 4).

In semi-arid climates, across irrigation methods and soil texture categories, irrigated agriculture increased SOC storage at the



**FIGURE 4** Change in soil organic carbon (SOC) stocks by study duration at the 0–10 cm depth increment for semi-arid, and sprinkler irrigated sites. Filled circles with error bars represent the mean change in SOC and their respective 95% CI. Where 95% CI does not overlap 0% (indicated by a vertical red line), SOC has significantly changed over time. The numbers to the right of each data point indicate the total number of observations used to calculate the mean

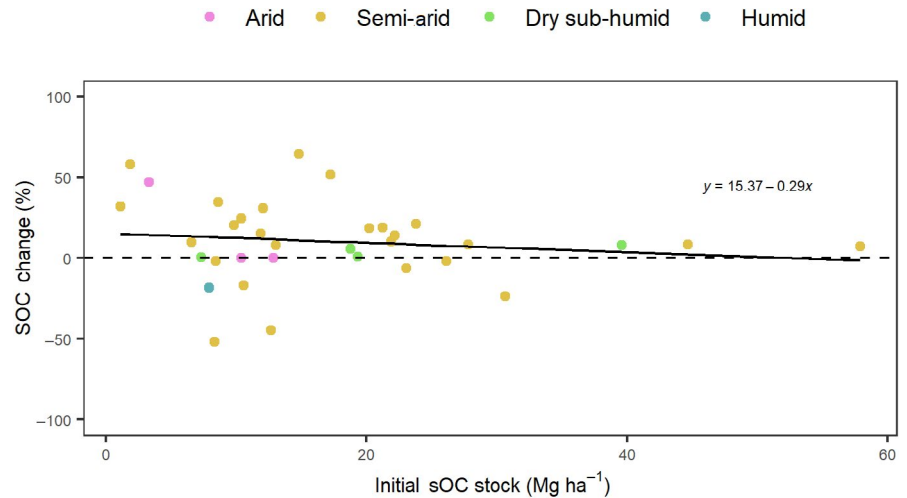
0–10 cm depth in short-term studies, but not in medium-term studies; only one study reported changes in SOC over the longer term. In sprinkler-irrigated systems, across climate types and soil texture categories, irrigated agriculture caused similar increases in SOC storage at the 0–10 cm depth over both the short and medium terms; again, only one study reported changes in SOC over the longer term. Clearly, longer-term monitoring of changes in SOC storage in irrigated systems is needed, although this analysis shows that even a few years of irrigation can cause changes in SOC.

We also examined the importance of study duration on changes in SOC storage by calculating the rate of change in SOC (i.e. % change in SOC divided by study duration; Supporting Information S12–S14), by depth increment. We found few discernible patterns in the data. At the 20–30 cm depth, however, SOC decreased significantly at a rate of  $-0.38\% \text{C year}^{-1}$  under drip irrigation (Supporting Information S14).

### 3.4 | Effects of initial SOC stock

There was a slight negative relationship between initial SOC stock and the % change of SOC in irrigated agriculture at the 0–10 cm depth ( $p = 0.04$ ), suggesting that irrigated agriculture is more likely to increase SOC in soils with lower initial SOC contents than in soils with higher initial SOC contents (Figure 5). Soils in arid climates tended to have lower initial SOC contents, while soils in semi-arid

**FIGURE 5** Change in soil organic carbon (SOC) stocks by initial SOC stock at the 0–10 cm depth increment for arid, semi-arid, dry sub-humid, and humid climate zones ( $R^2 = 0.0202$ ;  $p = 0.0423$ )



and dry sub-humid climates showed a wide range in initial SOC contents. It should be noted, however, that initial SOC stock explained only a very small portion of the variation in change in SOC stock ( $R^2 = 0.02$ ). No significant, discernible pattern was evident at greater soil depths (data not shown).

## 4 | DISCUSSION

This study assessed overall trends in SOC storage in irrigated agricultural systems across the globe by compiling and analysing data from 35 published studies (Supporting Information S1). In most cases, the studies used in this analysis (list of included studies can be found in Supporting Information S15) did not aim to examine the effects of irrigation on SOC per se, but were included in our meta-analysis because they reported data that could be used to assess the impact that irrigated agriculture has on SOC stocks across our study categories. The use of irrigation was the single unifying theme for selecting these studies to include in our analysis. We found that irrigated agriculture tends to increase SOC stocks (by 5.9% overall), and that the effects are strongest in surface soils. Of the 32 explanatory variables that we considered (Table 1), aridity and irrigation method had the strongest effect on the scale and direction of change in SOC under irrigated agriculture. Average annual precipitation, average annual temperature, elevation, crop type, and other management practices (e.g. tillage) had no or only minimal importance as explanatory variables. We also assessed the role of soil texture in mediating changes in SOC under irrigated agriculture, due to its well-documented importance in controlling SOC storage.

### 4.1 | Climate

Irrigation in arid and semi-arid regions was associated with larger increases in SOC than irrigation in wetter climates (although there were fewer data points for dry sub-humid and humid regions). Warmer

soil temperatures promote evapotranspiration, which drives irrigation water demand upward. Thus, more irrigation water was likely applied in studies conducted in arid/semi-arid regions than in more humid regions (Dong et al., 2015; Schütt et al., 2014). Irrigation in water-limited environments increases plant productivity, which can result in greater carbon inputs to the soil; however, wetting soils may also stimulate microbial activity, which can result in the loss of soil carbon due to increased mineralization of SOM (David et al., 2018; Dong et al., 2015). These two factors (increased plant productivity and accelerated microbial decay of SOM) thus act in opposite directions with respect to the accumulation of SOC. Our results indicate that the effect of irrigation on plant growth outweighs the effect on SOM decay by microbes (carbon mineralization), particularly in surface soils of arid and semi-arid regions.

Assuming that irrigated agriculture improves plant growth (via increased photosynthetic carbon fixation) and, consequently, surface litter and belowground (root) carbon inputs (Denef et al., 2008; Gillabel et al., 2007), the greatest improvements in SOC can be expected to extend from the soil surface to the maximum rooting depth, with smaller changes below the rooting zone (Troost et al., 2013). Data from semi-arid plots generally support this reasoning, with the greatest improvements in SOC at the 0–10 cm depth, smaller increases at the 20–30 cm depth, and no significant change at 10–20 and 30+ cm depths. By contrast, data from arid plots showed the greatest improvements in SOC at the 10–20 cm and the 30+ cm depths. Although available data for irrigated arid sites are clearly limited, this pattern might be expected for crops that root more deeply to scavenge for available water lower in the soil profile (Guswa, 2008). This finding is particularly relevant because SOC that accumulates at depth is considered relatively resistant to decomposition (Das et al., 2017; Minasny et al., 2017).

The contrasting changes in SOC storage at depth in arid and semi-arid sites could also reflect alterations in soil hydrology caused by the downward percolation of applied water. Again, such an effect would likely be strongest in the driest agricultural regions because of the requirement for more frequent and/or greater irrigation. Repeated wetting and drying, such as that which occurs over irrigation cycles,



can promote the formation of water-stable and micro-aggregates by altering cohesion and fragmentation processes in the soil; soil aggregation enhances both water-holding capacity and water infiltration (Trost et al., 2013). Improved infiltration of water can positively influence SOC storage at depth by translocating soluble carbon downward in the soil profile, where it can be readily sorbed onto unsaturated soil particles and, thus, protected from mineralization (Minasny et al., 2017; Tautges et al., 2019; Xu et al., 2016).

Few data have been published on the effects of irrigated agriculture on SOC storage in wetter climates, no doubt owing to the reduced need for irrigation in such regions. Our analysis detected a small, but significant, increase in SOC in irrigated dry sub-humid regions at the 0–10 cm depth but not at deeper depths, and a decrease in SOC at all depths in humid regions (although data were only available from one humid site). This is more or less in line with long-term (>10 years) studies conducted in sub-humid, humid, and tropical sites in Ethiopia and Brazil, which found no significant change in the SOC content with irrigation (De Bona et al., 2008; Getaneh et al., 2007). These studies were not included in our meta-analysis because they either did not report required study details (De Bona et al., 2008) or did not meet our criteria regarding consistent management practices (Getaneh et al., 2007), but their findings provide useful insights into the response of SOC to irrigation in wetter climates.

In their review of a number of long-term agricultural studies, Trost et al., (2013) reported that increases in SOC due to irrigation depended not only on climate but also on initial SOC levels: humid and semi-arid sites with higher initial SOC tended to show low or no increase in SOC storage while arid and semi-arid sites with lower initial SOC tended to show greater increases in SOC storage. While our analysis broadly supports a negative relationship between initial SOC storage and the scale and direction of changes in SOC storage in response to agricultural irrigation, this relationship was nuanced. While the greatest increases in SOC were indeed found in sites with lower initial SOC levels, so too were the greatest losses (Figure 5). The higher variability in changes in SOC storage observed for irrigated sites with initially lower SOC levels may simply be due to the fact that a greater number of studies have been conducted on sites with lower initial SOC stocks.

## 4.2 | Soil texture

Soils with a larger fine fraction tend to have a greater SOC storage capacity and, therefore, are expected to show greater increases in SOC due to irrigation (Wiesmeier et al., 2019; Zhong et al., 2018). With increases in clay content, irrigation is expected to favour formation of micro-aggregates (Trost et al., 2013; Wagner et al., 2007). As micro-aggregate formation increases, average pore size is decreased (Hassink et al., 1993). Since pore size determines accessibility of organic matter to microbes, a higher proportion of micro-pores has the potential to decrease SOC mineralization (Xu et al., 2016). Overall, there was a trend towards larger gains in SOC in soils with fine or medium textures than in soils with coarse textures, as

expected. However, SOC storage increased more consistently in medium-textured soils than in fine-textured soils, where SOC actually declined at the 10–20 and 30+ cm depths.

Differences in the response of SOC by soil depth in fine-textured soils may be associated, at least in part, with the downward translocation of soil particles during the percolation of irrigation water. In a study examining changes in soil properties of historically flood-irrigated fields that have been converted to drip irrigation, Puy et al., (2017) showed that soils directly under drippers had a higher ratio of coarse/fine particles than adjacent, unirrigated soils in the same field. This suggests that irrigation has the potential to shift SOC dynamics by translocating clay particles downward, thereby decreasing the proportion of the fine fraction in irrigated surface soils and altering soil hydrological properties at all depths (Warrington et al., 2007). Similarly, Drewry et al., (2020) found that soil bulk density increased, and macroporosity declined, in irrigated pastures and cropland in New Zealand. Further work examining changes in soil texture over time due to irrigation and at depth is necessary to better understand the role of soil texture in mediating irrigated agriculture-related changes in SOC, particularly on arid and semi-arid sites, where irrigation is employed most intensely.

## 4.3 | Irrigation method

The effect of irrigated agriculture on SOC storage also varied strongly by irrigation method and soil depth. In general, drip irrigation caused an increase in SOC storage in surface soils and a decrease in SOC storage below 10 cm, while sprinkler and flood furrow irrigation showed no consistent pattern with soil depth. Irrigation method likely plays an important role in determining the effects of irrigation on SOC content in agricultural soils by mediating changes in hydrological and physicochemical properties that vary with depth. In flood-irrigated agricultural plots established in the 10th–13th centuries current era that were converted to drip irrigation, areas directly under drippers showed increases in SOC and marked textural changes, as discussed in Section 4.2, whereas those adjacent to the drip zone lost SOC, likely due to increased SOC oxidation and reduced inputs of fresh plant biomass (Puy et al., 2017). Given that inputs of both water and fertilizer (e.g. via fertigation) are much more localized under drip irrigation, the positive effects of irrigation on SOC are limited to those areas directly under the drippers (Kallenbach et al., 2010; Puy et al., 2017; Sánchez-Martín et al., 2008). Differences in the distribution of water among irrigation methods (i.e. highly localized under drip irrigation vs. more uniform under flood/furrow and sprinkler irrigation) may account for the observed differences in SOC contents among irrigation methods reported here. This raises the possibility that soil sampling strategies influenced our results. For example, the drip irrigation studies included in our meta-analysis largely employed composite sampling, which included randomized sample locations across a plot, without defining whether those samples came from the 'wetted bulb' under the drippers; only one study specified that sampling was conducted

directly within the drip zone. To properly capture the effects of drip irrigation on SOC from the perspective of atmospheric greenhouse gas mitigation and large-scale carbon stocks, sampling must be designed to represent the entire gradient of soil moisture contents across each plot.

Soil organic carbon stocks under drip-irrigated agriculture decreased with depth in our analysis; however, it is difficult to know whether this reflects the sampling issues outlined above. Nevertheless, given the results from Puy et al., (2017), it seems likely that the pattern shown in Figure 3 is a reasonable representation of field-scale effects of drip irrigation on SOC. In addition to the highly localized placement of water caused by drip irrigation, careful control of irrigation volumes to prevent deep percolation of water under drip irrigation restricts drainage of water beyond the rooting zone (Sanchez-Martín et al., 2010). Therefore, the observed decrease in SOC at depth is likely due to decreased microbial activity and/or reduced root inputs outside the 'wetted bulb' beneath drip emitters (Liu et al., 2008; Wiesmeier et al., 2019).

Less spatially discrete irrigation methods, such as flood/furrow and sprinkler irrigation, can increase the availability of soil water to both crop- and non-crop plant species. Indeed, the largest gains in SOC storage were observed in surface soils under sprinkler irrigation, which generally applies water across the entire surface of an agricultural field (i.e. to both crop and non-crop plants). While the growth of weeds and other non-crop plants may be counter to the objectives of conventionally managed/precision agriculture, they can also contribute to increased SOC stocks (Moonen & Bàrberi, 2008; Petit et al., 2011). For example, inter-row spaces in orchards and vineyards are increasingly recognized as valuable targets for enhancing SOC stocks in agricultural soils (Midwood et al., 2020; Puy et al., 2017; Trost et al., 2013). Shifting the SOC dynamic for a whole agricultural field via irrigation may have notable benefits for long-term SOC change in agricultural soils, but the inherent inefficiency of applying irrigation water to support the growth of both crop- and non-crop species may not be sustainable as global demand for irrigation water increases (Levidow et al., 2014; Puy et al., 2017; The United Nations World Water Development, 2014). As such, historically flood-irrigated agricultural fields are increasingly transitioning to more efficient drip irrigation systems (Puy et al., 2017). While this shift to drip irrigation may increase water use efficiency and decrease infrastructure-related CO<sub>2</sub> emissions, our results demonstrate that there are potentially far-reaching environmental trade-offs (i.e. reductions in SOC storage in deeper horizons) involved in adopting precision irrigation practices on a global scale.

#### 4.4 | Limitations and potential for future study direction

Our data show that, overall, irrigated agriculture can increase SOC at all depths, but effects vary widely among climate categories, soil textures, and irrigation methods. Our results show that in semi-arid

sites, SOC increased across the full soil profile under irrigated agriculture (Figure 3), but it remains unclear whether increases in SOC due to irrigated agriculture are sufficient to reverse the frequently reported losses of SOC caused by the conversion of natural, unmanaged ecosystems to agricultural systems. Furthermore, increased SOC was associated with fine- and medium-textured soils at the 0–10 cm depth but patterns were less clear in deeper soils, suggesting that downward percolation of finer-textured particles may play an important role (Puy et al., 2017; Warrington et al., 2007). Observed differences in the pattern of change in SOC storage among irrigation methods, by contrast, offer direct insights into the effects of agricultural management practices on soil C dynamics but also highlights the difficulty in balancing management to maximize SOC storage and other environmental considerations, such as protecting water availability (Puy et al., 2017; Velasco-Munoz et al., 2019). Consequently, any prescriptive changes in irrigation management practices aimed at increasing SOC stocks must consider resource availability and the interactive effects of other management practices that are not directly discussed here.

In their review, Trost et al.,(2013) estimated that irrigation of semi-arid sites can increase SOC storage by 11%–35%. Trost et al., (2013) used different inclusion criteria for their calculations: they included comparisons of rainfed and irrigated fields and comparisons of un-cultivated and irrigated fields, which we systematically excluded from our analysis because of low study numbers and confounding effects such as differences in plant species (i.e. agronomic vs. native species), and the effect of land-use conversion. Furthermore, it is unclear to what soil depths the estimates reported in Trost et al., (2013) are referring. However, our calculation of a 14.8% increase in SOC stocks at the 0–10 cm depth on semi-arid sites falls within their estimated range. That being said, we calculated much smaller gains in the full profile (8.0%) and deeper soil increments on semi-arid sites (4.1% increase at the 20–30 cm depth and no significant change at the 10–20 and 30+ cm depths).

This analysis brought to light critical gaps in the available data regarding irrigated agriculture across the globe. Despite its importance in soil dynamics, bulk density (BD) data were notably absent in a large number of studies. As such, considerable effort was required to accurately estimate bulk density values when they were not provided. Similarly, standard error or standard deviation data were often missing and required post hoc estimates from the assembled dataset. Any sort of gap-filling introduces uncertainty into the dataset and, as such, we recommend that this sort of data is reported in all future studies.

Additionally, a majority of studies did not report SOC values beyond near-surface depths. While we recognize that the greatest changes in SOC related to agricultural management practices are likely to occur near the soil surface, studies are increasingly showing that the overall effects of agricultural management and, in particular, irrigation, on SOC stocks are vastly misrepresented when only surface depths are considered (McNally et al., 2017; Mudge et al., 2017; Schipper et al., 2017; Trost et al., 2013). We therefore believe it is important that future studies include deeper sampling where possible.

Finally, information regarding irrigated agricultural plots over longer duration (>15 years) was notably limited, with 50% of the assembled studies being 5 years or less in duration, 39% being 15 years or less, and only 11% being longer than 15 years. Long-term studies meeting our study criteria were particularly absent for arid, dry sub-humid, and humid climate categories as well as for drip-irrigated plots. Furthermore, while the literature often refers to the role of soil texture in SOC storage (Saiz et al., 2012; Trost et al., 2013; Wiesmeier et al., 2019; Zhong et al., 2018), few discuss the effect of irrigation on changes in soil texture and the subsequent translocation of clay through the soil profile over the long term (Puy et al., 2017; Xu et al., 2016). Understanding how SOC dynamics are affected by translocation of clay (and nutrients) in response to irrigation practices is important to enhance the efficacy of global efforts aimed at offsetting greenhouse gas emissions via SOC sequestration.

In summary, we compiled and analysed data from 35 published studies that reported SOC stocks at the beginning and end of experiments conducted in irrigated agricultural systems across the globe. We found that irrigated agriculture tends to increase SOC stocks, particularly in surface soils, in fine- to medium-textured soils, in arid to semi-arid climates and under sprinkler irrigation. Although numerous other variables, for example, crop type, crop residue removal, and tillage practices, have been shown to have important effects on SOC storage, particularly in regional-scale studies, they were not significant contributors to the patterns of change in SOC storage observed under irrigated agriculture in this global-scale analysis. Annual precipitation, annual temperature, and elevation also had no or only minimal value as explanatory variables. These findings demonstrate the value of considering aridity, irrigation method, and soil texture for future assessments of global-scale changes in SOC storage under irrigated agriculture.

#### ACKNOWLEDGEMENTS

This work was funded by the Agricultural Greenhouse Gases Program of Agriculture and Agri-food Canada (Project AAGP2-25). Dr. Songchao Chen and Dr. Stephen I.C. Akpa provided R code snippets and advice in estimating bulk density values. Skye Wills similarly provided the R code snippets used in Sequeira et al., (2014) for estimating bulk density values. We are grateful to Ryan Stewart for putting us in touch with Jinshin Jian who provided us with R code snippets for generating multi-figure forest plots.

#### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Open Science Framework (OSF) at <http://doi.org/10.17605/OSF.IO/EVCSH>.

#### ORCID

David Emde  <https://orcid.org/0000-0002-7311-3159>

#### REFERENCES

- Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment*, 168, 25–36. <https://doi.org/10.1016/j.agee.2013.02.003>
- Akpa, S. I. C., Ugbaje, S. U., Bishop, T. F. A., & Odeh, I. O. A. (2016). Enhancing pedotransfer functions with environmental data for estimating bulk density and effective cation exchange capacity in a data-sparse situation. *Soil Use and Management*, 32(4), 644–658. <https://doi.org/10.1111/sum.12310>
- Andrews, D. M., Robb, T., Elliott, H., & Watson, J. E. (2016). Impact of long-term wastewater irrigation on the physicochemical properties of humid region soils: “The Living Filter” site case study. *Agricultural Water Management*, 178, 239–247. <https://doi.org/10.1016/j.agwat.2016.10.001>
- Angers, D. A., & Eriksen-Hamel, N. S. (2008). Full-inversion tillage and organic carbon distribution in soil profiles: A meta-analysis. *Soil Science Society of America Journal*, 72, 1370–1374. <https://doi.org/10.2136/sssaj2007.0342>
- Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Tao, B., Hui, D., Yang, J., & Matocha, C. (2019). Responses of soil carbon sequestration to climate smart agriculture practices: A meta-analysis. *Global Change Biology*, 25(8), 2591–2606. <https://doi.org/10.1111/gcb.14658>
- Bashir, Y., & Conlon, K. C. (2018). Step by step guide to do a systematic review and meta-analysis for medical professionals. *Irish Journal of Medical Science*, 187(2), 447–452. <https://doi.org/10.1007/s11845-017-1663-3>
- Chen, S., Richer-de-Forges, A. C., Saby, N. P. A., Martin, M. P., Walter, C., & Arrouays, D. (2018). Building a pedotransfer function for soil bulk density on regional dataset and testing its validity over a larger area. *Geoderma*, 312, 52–63. <https://doi.org/10.1016/j.geoderma.2017.10.009>
- Condon, L. M., Hopkins, D. W., Gregorich, E. G., Black, A., & Wakelin, S. A. (2014). Long-term irrigation effects on soil organic matter under temperate grazed pasture: Pasture production and soil organic matter. *European Journal of Soil Science*, 65(5), 741–750. <https://doi.org/10.1111/ejss.12164>
- Das, D., Dwivedi, B. S., Singh, V. K., Datta, S. P., Meena, M. C., Chakraborty, D., Bandyopadhyay, K. K., Kumar, R., & Mishra, R. P. (2017). Long-term effects of fertilisers and organic sources on soil organic carbon fractions under a rice-wheat system in the Indo-Gangetic Plains of north-west India. *Soil Research*, 55(3), 296–308. <https://doi.org/10.1071/SR16097>
- David, C., Lemke, R., Helgason, W., & Farrell, R. E. (2018). Current inventory approach overestimates the effect of irrigated crop management on soil-derived greenhouse gas emissions in the semi-arid Canadian Prairies. *Agricultural Water Management*, 208, 19–32. <https://doi.org/10.1016/j.agwat.2018.06.006>
- De Bona, F. D., Bayer, C., Dieckow, J., & Bergamaschi, H. (2008). Soil quality assessed by carbon management index in a subtropical Acrisol subjected to tillage systems and irrigation. *Soil Research*, 46(5), 469–475. <https://doi.org/10.1071/SR08018>
- Denef, K., Stewart, C. E., Brenner, J., & Paustian, K. (2008). Does long-term center-pivot irrigation increase soil carbon stocks in semi-arid agro-ecosystems? *Geoderma*, 145(1), 121–129. <https://doi.org/10.1016/j.geoderma.2008.03.002>
- Dersch, G., & Böhm, K. (2001). Effects of agronomic practices on the soil carbon storage potential in arable farming in Austria. *Nutrient Cycling in Agroecosystems*, 60, 49–55. <https://doi.org/10.1023/A:1012607112247>
- Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks – A meta-analysis. *Global Change Biology*, 17(4), 1658–1670. <https://doi.org/10.1111/j.1365-2486.2010.02336.x>
- Dong, L., Yu, D., Zhang, H., Zhang, M., Jin, W., Liu, Y., & Shi, X. (2015). Long-term effect of sediment laden Yellow River irrigation water on soil organic carbon stocks in Ningxia, China. *Soil and*

- Tillage Research*, 145, 148–156. <https://doi.org/10.1016/j.still.2014.09.009>
- Drewry, J. J., Carrick, S., Penny, V., Houlbrooke, D. J., Laurenson, S., & Mesman, N. L. (2020). Effects of irrigation on soil physical properties in predominantly pastoral farming systems: A review. *New Zealand Journal of Agricultural Research*, 1–25. <https://doi.org/10.1080/00288233.2020.1742745>
- Du, Z., Angers, D. A., Ren, T., Zhang, Q., & Li, G. (2017). The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis. *Agriculture, Ecosystems & Environment*, 236, 1–11. <https://doi.org/10.1016/j.agee.2016.11.007>
- Ellmer, F., & Baumecker, M. (2002). 65 years long-term experiments at Thyrö. Results for sustainable crop production at sandy soils. *Archives of Agronomy and Soil Science*, 48(5), 521–531. <https://doi.org/10.1080/03650340215639>
- Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1 km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), 4302–4315. <https://doi.org/10.1002/joc.5086>
- Field, A. P., & Gillett, R. (2010). How to do a meta-analysis. *The British Journal of Mathematical and Statistical Psychology*, 63(Pt 3), 665–694. <https://doi.org/10.1348/000711010X502733>
- Getaneh, F., Deressa, A., & Negassa, W. (2007). Influence of small scale irrigation on selected soil chemical properties. In *Utilization of diversity in land use systems: Sustainable and organic approaches to meet human needs*. Tropentag.
- Gillabel, J., Deneff, K., Brenner, J., Merckx, R., & Paustian, K. (2007). Carbon sequestration and soil aggregation in center-pivot irrigated and dryland cultivated farming systems. *Soil Science Society of America Journal*, 71, 1020–1028. <https://doi.org/10.2136/sssaj2006.0215>
- Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: A meta analysis. *Global Change Biology*, 8(4), 345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>
- Gurevitch, J., Koricheva, J., Nakagawa, S., & Stewart, G. (2018). Meta-analysis and the science of research synthesis. *Nature*, 555(7695), 175–182. <https://doi.org/10.1038/nature25753>
- Guswa, A. J. (2008). The influence of climate on root depth: A carbon cost-benefit analysis. *Water Resources Research*, 44, W02427. <https://doi.org/10.1029/2007WR006384>
- Halupka, L., & Halupka, K. (2017). The effect of climate change on the duration of avian breeding seasons: A meta-analysis. *Proceedings of the Royal Society B: Biological Sciences*, 284(1867). <https://doi.org/10.1098/rspb.2017.1710>
- Häring, V., Manka'abusi, D., Akoto-Danso, E. K., Werner, S., Atiah, K., Steiner, C., Lompo, D. J. P., Adiku, S., Buerkert, A., & Marschner, B. (2017). Effects of biochar, waste water irrigation and fertilization on soil properties in West African urban agriculture. *Scientific Reports*, 7(1), 10738. <https://doi.org/10.1038/s41598-017-10718-y>
- Hassink, J., Bouwman, L. A., Zwart, K. B., & Brussaard, L. (1993). Relationships between habitable pore space, soil biota and mineralization rates in grassland soils. *Soil Biology and Biochemistry*, 25(1), 47–55. [https://doi.org/10.1016/0038-0717\(93\)90240-C](https://doi.org/10.1016/0038-0717(93)90240-C)
- Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, 80(4), 1150–1156. [https://doi.org/10.1890/0012-9658\(1999\)080\[1150:TMAOR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[1150:TMAOR]2.0.CO;2)
- Jerabkova, L., Prescott, C. E., Titus, B. D., Hope, G. D., & Walters, M. B. (2011). A meta-analysis of the effects of clearcut and variable-retention harvesting on soil nitrogen fluxes in boreal and temperate forests. *Canadian Journal of Forest Research*, 41(9), 1852–1870. <https://doi.org/10.1139/x11-087>
- Jian, J., Du, X., Reiter, M. S., & Stewart, R. D. (2020). A meta-analysis of global cropland soil carbon changes due to cover cropping. *Soil Biology and Biochemistry*, 143, 107735. <https://doi.org/10.1016/j.soilbio.2020.107735>
- Kallenbach, C. M., Rolston, D. E., & Horwath, W. R. (2010). Cover cropping affects soil N<sub>2</sub>O and CO<sub>2</sub> emissions differently depending on type of irrigation. *Agriculture, Ecosystems & Environment*, 137(3), 251–260. <https://doi.org/10.1016/j.agee.2010.02.010>
- Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., & Scardigno, A. (2014). Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agricultural Water Management*, 146, 84–94. <https://doi.org/10.1016/j.agwat.2014.07.012>
- Liu, C., Holst, J., Brüggemann, N., Butterbach-Bahl, K., Yao, Z., Han, S., Han, X., & Zheng, X. (2008). Effects of irrigation on nitrous oxide, methane and carbon dioxide fluxes in an Inner Mongolian steppe. *Advances in Atmospheric Sciences*, 25(5), 748–756. <https://doi.org/10.1007/s00376-008-0748-3>
- McGill, B. M., Hamilton, S. K., Millar, N., & Robertson, G. P. (2018). The greenhouse gas cost of agricultural intensification with groundwater irrigation in a Midwest US row cropping system. *Global Change Biology*, 24(12), 5948–5960. <https://doi.org/10.1111/gcb.14472>
- McNally, S. R., Beare, M. H., Curtin, D., Meenken, E. D., Kelliher, F. M., Calvelo Pereira, R., Shen, Q., & Baldock, J. (2017). Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. *Global Change Biology*, 23(11), 4544–4555. <https://doi.org/10.1111/gcb.13720>
- Midwood, A. J., Hannam, K. D., Forge, T. A., Neilsen, D., Emde, D., & Jones, M. D. (2020). Importance of drive-row vegetation for soil carbon storage in woody perennial crops: A regional study. *Geoderma*, 377, 114591. <https://doi.org/10.1016/j.geoderma.2020.114591>
- Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., ... Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, 292, 59–86. <https://doi.org/10.1016/j.geoderma.2017.01.002>
- Moonen, A.-C., & Bàrberi, P. (2008). Functional biodiversity: An agroecosystem approach. *Agriculture, Ecosystems & Environment*, 127(1), 7–21. <https://doi.org/10.1016/j.agee.2008.02.013>
- Mudge, P. L., Kelliher, F. M., Knight, T. L., O'Connell, D., Fraser, S., & Schipper, L. A. (2017). Irrigating grazed pasture decreases soil carbon and nitrogen stocks. *Global Change Biology*, 23(2), 945–954. <https://doi.org/10.1111/gcb.13448>
- Ogle, S. M., Breidt, F. J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, 72(1), 87–121. <https://doi.org/10.1007/s10533-004-0360-2>
- Parchami, A. (2016). *Weighted.Desc.Stat: Weighted descriptive statistics*. <https://CRAN.R-project.org/package=Weighted.Desc.Stat>
- Petit, S., Boursault, A., Le Guilloux, M., Munier-Jolain, N., & Reboud, X. (2011). Weeds in agricultural landscapes. A review. *Agronomy for Sustainable Development*, 31(2), 309–317. <https://doi.org/10.1051/agro/2010020>
- Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J., & Gensior, A. (2011). Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach. *Global Change Biology*, 17(7), 2415–2427. <https://doi.org/10.1111/j.1365-2486.2011.02408.x>
- Puy, A., Garcia Aviles, J. M., Balbo, A. L., Keller, M., Riedesel, S., Blum, D., & Bubbenzer, O. (2017). Drip irrigation uptake in traditional irrigated fields: The edaphological impact. *Journal of Environmental Management*, 202, 550–561. <https://doi.org/10.1016/j.jenvman.2016.07.017>
- R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Ramirez-Fuentes, E., Lucho-constantino, C., Escamilla-Silva, E., & Dendooven, L. (2002). Characteristics, and carbon and nitrogen dynamics in soil irrigated with wastewater for different lengths

- of time. *Bioresource Technology*, 85(2), 179–187. [https://doi.org/10.1016/S0960-8524\(02\)00035-4](https://doi.org/10.1016/S0960-8524(02)00035-4)
- Rosenberg, M. S. (2005). The file-drawer problem revisited: A general weighted method for calculating fail-safe numbers in meta-analysis. *Evolution*, 59(2), 464–468. <https://doi.org/10.1111/j.0014-3820.2005.tb01004.x>
- Rotenberg, D., Cooperband, L., & Stone, A. (2005). Dynamic relationships between soil properties and foliar disease as affected by annual additions of organic amendment to a sandy-soil vegetable production system. *Soil Biology and Biochemistry*, 37(7), 1343–1357. <https://doi.org/10.1016/j.soilbio.2004.12.006>
- Rusinamhodzi, L., Corbeels, M., van Wijk, M. T., Rufino, M. C., Nyamangara, J., & Giller, K. E. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development*, 31(4), 657–673. <https://doi.org/10.1007/s13593-011-0040-2>
- Sainju, U. M., Stevens, W. B., Caesar-TonThat, T., Liebig, M. A., & Wang, J. (2014). Net global warming potential and greenhouse gas intensity influenced by irrigation, tillage, crop rotation, and nitrogen fertilization. *Journal of Environmental Quality*, 43(3), 777–788.
- Saiz, G., Bird, M. I., Domingues, T., Schrodt, F., Schwarz, M., Feldpausch, T. R., Veenendaal, E., Djagbletey, G., Hien, F., Compaore, H., Diallo, A., & Lloyd, J. (2012). Variation in soil carbon stocks and their determinants across a precipitation gradient in West Africa. *Global Change Biology*, 18(5), 1670–1683. <https://doi.org/10.1111/j.1365-2486.2012.02657.x>
- Sánchez-Martín, L., Arce, A., Benito, A., García-Torres, L., & Vallejo, A. (2008). Influence of drip and furrow irrigation systems on nitrogen oxide emissions from a horticultural crop. *Soil Biology and Biochemistry*, 40(7), 1698–1706. <https://doi.org/10.1016/j.soilbio.2008.02.005>
- Sanchez-Martín, L., Meijide, A., García-Torres, L., & Vallejo, A. (2010). Combination of drip irrigation and organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate. *Agriculture, Ecosystems & Environment*, 137(1), 99–107. <https://doi.org/10.1016/j.agee.2010.01.006>
- Schipper, L. A., Mudge, P. L., Kirschbaum, M. U. F., Hedley, C. B., Golubiewski, N. E., Smaill, S. J., & Kelliher, F. M. (2017). A review of soil carbon change in New Zealand's grazed grasslands. *New Zealand Journal of Agricultural Research*, 60(2), 93–118. <https://doi.org/10.1080/00288233.2017.1284134>
- Schütt, M., Borken, W., Spott, O., Stange, C. F., & Matzner, E. (2014). Temperature sensitivity of C and N mineralization in temperate forest soils at low temperatures. *Soil Biology and Biochemistry*, 69, 320–327. <https://doi.org/10.1016/j.soilbio.2013.11.014>
- Sequeira, C. H., Wills, S. A., Seybold, C. A., & West, L. T. (2014). Predicting soil bulk density for incomplete databases. *Geoderma*, 213, 64–73. <https://doi.org/10.1016/j.geoderma.2013.07.013>
- Tautges, N. E., Chiartas, J., Gaudin, A. C. M., O'Geen, A. T., Herrera, I., & Scow, M. K. (2019). Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and sub-surface soils. *Global Change Biology*, 25(11), 3753–3766. <https://doi.org/10.1111/gcb.14762>
- Telo da Gama, J., Rato Nunes, J., Loures, L., Lopez Piñeiro, A., & Vivas, P. (2019). Assessing spatial and temporal variability for some edaphic characteristics of Mediterranean rainfed and irrigated soils. *Agronomy*, 9(3), 132. <https://doi.org/10.3390/agronomy9030132>
- The United Nations World Water Development. (2014). *The United Nations World Water Development report 2014*. <http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-24-irrigated-land/>
- Trabucco, A., & Zomer, R. J. (2018). Global Aridity Index and potential Evapo-Transpiration (ETO) Climate Database v2. In *CGIAR Consortium for Spatial Information (CGIAR-CSI)*. Available online [https://figshare.com/articles/Global\\_Aridity\\_Index\\_and\\_Potential\\_Evapotranspiration\\_ETO\\_Climate\\_Database\\_v2/7504448/1](https://figshare.com/articles/Global_Aridity_Index_and_Potential_Evapotranspiration_ETO_Climate_Database_v2/7504448/1)
- Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., & Baumecker, M. (2013). Irrigation, soil organic carbon and N<sub>2</sub>O emissions. A review. *Agronomy for Sustainable Development*, 33(4), 733–749. <https://doi.org/10.1007/s13593-013-0134-0>
- Undersander, D. J., & Ger, Cecil Rei (1985). Management on continuous production of irrigated winter wheat. *Agronomy journal*, 77, 508–511.
- Velasco-Munoz, J. F., Aznar-Sanchez, J. A., Batlles-de-laFuente, A., & Fidelibus, M. D. (09/ 2019). Sustainable irrigation in agriculture: An analysis of global research. *Water*, 11(9), 1758. <https://doi.org/10.3390/w11091758>
- Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, 36(3), 1–48.
- Wagner, S., Cattle, S. R., & Scholten, T. (2007). Soil-aggregate formation as influenced by clay content and organic-matter amendment. *Journal of Plant Nutrition and Soil Science*, 170(1), 173–180. <https://doi.org/10.1002/jpln.200521732>
- Warrington, D. N., Goldstein, D., & Levy, G. J. (2007). Clay translocation within the soil profile as affected by intensive irrigation with treated wastewater. *Soil Science*, 172(9), 692–700. <https://doi.org/10.1097/SS.0b013e3180d0a43d>
- Wei, X., Shao, M., Gale, W., & Li, L. (2014). Global pattern of soil carbon losses due to the conversion of forests to agricultural land. *Scientific Reports*, 4, 4062. <https://doi.org/10.1038/srep04062>
- Wiesmeier, M., Poeplau, C., Sierra, C. A., Maier, H., Frühauf, C., Hübner, R., Kühnel, A., Spörlein, P., Geuß, U., Hangen, E., Schilling, B., von Lützw, M., & Kögel-Knabner, I. (2016). Projected loss of soil organic carbon in temperate agricultural soils in the 21(st) century: effects of climate change and carbon input trends. *Scientific Reports*, 6, 32525.
- Wiesmeier, M., Urbanski, L., Hobbey, E., Lang, B., von Lützw, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H.-J., & Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils – A review of drivers and indicators at various scales. *Geoderma*, 333, 149–162. <https://doi.org/10.1016/j.geoderma.2018.07.026>
- Xu, H., Sieverding, H., Kwon, H., Clay, D., Stewart, C., Johnson, J. M. F., Qin, Z., Karlen, D. L., & Wang, M. (2019). A global meta-analysis of soil organic carbon response to corn stover removal. *GCB Bioenergy*, 11(10), 1215–1233. <https://doi.org/10.1111/gcbb.12631>
- Xu, X., Shi, Z., Li, D., Rey, A., Ruan, H., Craine, J. M., Liang, J., Zhou, J., & Luo, Y. (2016). Soil properties control decomposition of soil organic carbon: Results from data-assimilation analysis. *Geoderma*, 262, 235–242. <https://doi.org/10.1016/j.geoderma.2015.08.038>
- Zhong, Z., Chen, Z., Xu, Y., Ren, C., Yang, G., Han, X., Ren, G., & Feng, Y. (2018). Relationship between soil organic carbon stocks and clay content under different climatic conditions in central China. *Forests, Trees and Livelihoods*, 9(10), 598. <https://doi.org/10.3390/f9100598>

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

**How to cite this article:** Emde D, Hannam KD, Most I, Nelson LM, Jones MD. Soil organic carbon in irrigated agricultural systems: A meta-analysis. *Glob Change Biol*. 2021;27:3898–3910. <https://doi.org/10.1111/gcb.15680>