INTRODUCTION

The United States agricultural industry contributed 992 billion dollars to GDP in 2015 and supports 11% of the country's employment (Bureau of Economic Analysis, 2017). Agriculture is also responsible for 80% of US consumptive water each year (Bureau of Economic Analysis, 2018). Concerns related to water scarcity highlight the importance of methods to reduce agricultural water use. As such, it is salient to constrain the extent to which innovations such as biochar soil amendment can provide benefits.

Biochar is charcoal intentionally made for soil amendment. It is generally created by pyrolyzing organic materials, though there are large variations in feedstock, reactor...
residence time, and type of reactor. When added to soil, biochar increases nutrient and water retention (Laird et al., 2010; Ulvett et al., 2013), helps increase yield in both staple and specialty crops (Arif et al., 2015; Crane-Droesch et al., 2013; Dumortier et al., 2020; Kätterer et al., 2019), and acts as a greenhouse gas sink (Dumortier et al., 2020; Kammann et al., 2011; Kammann et al., 2017; Windeatt et al., 2014; Woolf et al., 2010).

Because the best-documented biochar benefit for soil hydraulics is improvement in water holding capacity (WHC), we used this property as a first metric for evaluating the breadth of soil water benefits that can occur following biochar addition. WHC is defined as the amount of water held at −33 bar, or operationally as the amount of water remaining in a soil after allowing saturated soil to drain for a set period of time (typically 30 min). WHC includes water that is not available for plants to use (held beyond permanent wilting point), as well as plant available water (PAW), which is water held between WHC and the permanent wilting point (Weil & Brady, 2006). WHC varies between soils of different texture, with clay soils having a higher WHC than sandy soils (Weil & Brady, 2006).

Changes in water retention with biochar application result predominantly from changes in the packing efficiency of soil particles that occur when biochar is added. Depending on the relative sizes of biochar particles and soil grains, biochar amendment could theoretically increase or decrease soil pore space, with an increase in WHC occurring when biochar particles are sized and shaped such that, when added to original soil matrices, they create new pore spaces in the matrix packing. In practice it is expensive to grind biochar particles finely enough to clog soil pores, and because of this, most studies report an increase in WHC driven by an increase in the space between biochar particles and soil particles (interpores). These interpores can hold water past the original capacity of the unamended soil (Liao & Thomas, 2019; Phillips et al., 2020). Biochar particles that are a different diameter from the host soil, as well as those having a high aspect ratio (narrow and long) are most efficient at disrupting the packing of soil grains and creating new pore spaces, leading to an increase in overall water storage and WHC (Fischer et al., 2019; Liao & Thomas, 2019; Phillips et al., 2020).

A secondary increase in porosity derives from the extensive pore structure in the biochar particles themselves. The space inside biochar particles (termed intrapores) derives from the remnants of plant cell walls and can secondarily be influenced by pyrolysis conditions (Liu et al., 2017). These intrapores can hold water at a plant available potential and increase soil water content directly (Liu, Dugan, et al., 2016; Liu, Wang, et al., 2016; Liu, Wang, et al., 2016; Liu, et al., 2017). Biochar intrapore connectivity, which is influenced by the porosity of the biochar itself due to feedstock and pyrolysis method, has been shown to increase WHC (Liu, Dugan, et al., 2016; Liu, Wang, et al., 2016; Yi et al., 2020).

Our meta-analysis uses a statistical multivariate regression analysis of biochar-driven WHC changes which we used to build a model of the relationship between biochar properties, production conditions, and application rates. We also discuss the connection between predicted WHC increases and irrigation quantities and costs. This then allowed us to map the potential water saving benefit from biochar across the US at the county level, considering the existing variability in soil texture. We discuss benefits of increased WHC that could accrue in the agricultural sector with biochar use and how those financial benefits could be calculated for specific land owners. By connecting biochar's properties to estimation methods and socioeconomic benefits we hope to provide direction and support for future biochar research and development, as well as guidance for biochar consumers and decision makers in the agricultural sector.

2 | MATERIALS AND METHODS

We collected data on WHC changes following biochar amendment from existing peer-reviewed studies. Although there is a large body of literature on biochar effects on soil water properties, relatively few studies report all the minimum set of variables we determined necessary for our analysis: biochar feedstock, pyrolysis temperature, biochar particle size, soil texture percentages, application rate of biochar, and, as the dependent variable, observed change in WHC. We chose these variables because they are the most commonly available to biochar stakeholders. Therefore it was necessary to narrow our data set to include this cultivated list of variables with which to establish variable relationships. This decreased the number of studies used to 16 (Amoakwah et al., 2017; Baronti et al., 2014; Dugan et al., 2010; Glad et al., 2016; Hansen et al., 2016; Hardie et al., 2014; Kammann et al., 2011; Karhu et al., 2011; Liu, Dugan, et al., 2016; Liu, Wang, et al., 2016; Mangrich et al., 2015; Nelissen et al., 2015; Novak et al., 2012; Peake et al., 2014; Saarnio et al., 2013; Wang et al., 2019; Yu et al., 2013). Nine of the studies that were originally amassed were not included in our overall analysis because they excluded one or more of the required variables (detailed collected information provided in the Supporting Information). We investigated the relationships between these variables and WHC change using multivariate regression analysis with Excel and STATA, correcting for heteroskedasticity (Verardi & Croux, 2009).

We recorded biochar particle size in millimeters (mm), application rate in tons per hectare, and observed change in WHC as a percentage change from non-altered soil. Biochar feedstock and pyrolysis temperature were each recorded categorically, with feedstock separated into five categories (woody, straw, shell, grass, and non-traditional) and pyrolysis temperature into three levels (low: 300−450°C; medium:
450–700°C; high: >700°C). Biochar feedstock is included in our analysis because it can influence biochar porosity and potentially the interface of the biochar and water (Harvey et al., 2011; Masek, 2016). Pyrolysis temperature is a primary determinant of the amount of biochar made in a production cycle, but some studies conclude that higher temperatures may produce biochar with a larger quantity of micropores (Brewer et al., 2014; Lopez-Capel, 2016). Biochar feedstock and temperature can operate together to influence hydrologic properties (Sanchez-Garcia et al., 2019). Therefore, we include temperature as a variable in our regression to test this within our own data set.

We include biochar soil application rate because it varies greatly in peer-reviewed studies and represents the primary cost determination of biochar use. Information regarding soil texture is also in the analysis because soil texture (sand, silt, and clay content) is a determinant of base WHC due to grain size packing, so it may be a control on observed changes with biochar (Liu et al., 2017).

Our analysis focuses on WHC changes following biochar addition primarily because WHC is the most commonly reported water property in biochar literature. PAW is a more direct measure of water retention benefit for plants, but it is more difficult to measure and thus less frequently reported. PAW was reported in only 43% of our collected studies, and only 20% of those studies that reported PAW contained the variables that we use in our regression analysis. Thus, we assume for the purposes of this analysis that increases in WHC are highly correlated with increases in PAW (Edeh et al., 2020). This assumption is supported for sandy soils by research that shows increases in WHC with biochar use occur within the range of PAW (Edeh et al., 2020; Liu et al., 2017). Our collected data points are concentrated in sandy soil environments (Figure 1), making this assumption reasonable for the specific data set used herein. However, this assumption brings the caveat that results of our meta-analysis may only hold for sandy soils.

3 | RESULTS

We use ordinary least squares (OLS) as a first pass to analyze the effect of the data on WHC (Table 1). The regression revealed a high adjusted $R^2$ value of .8902, indicating the included variables in the regression account for around 90% of the observed variability in WHC.

![Soil Textural Triangle](image)

**FIGURE 1** Soil texture data points plotted on soil textural triangle. Data used in this study are plotted on the USDA soil textural triangle. Most are from sandy soils.

**TABLE 1** Ordinary least squares (OLS) regression of meta-data

| Variable          | Coefficient | SE    | T     | $p > |t|$ | 95% confidence interval |
|-------------------|------------|-------|-------|-------|-------------------------|
| One-sand %        | −2.1729    | 0.4346| −5.00 | .000  | −3.0337                 | −1.3121 |
| Application rate  | 0.7264     | 0.0263| 27.62 | .000  | 0.6743                  | 0.7785 |
| Particle size     | 2.1658     | 22.7480| 0.10 | .924  | −42.8854                | 47.2170 |
| Low temp          | 4.0657     | 52.0367| 0.08 | .938  | −98.9903                | 107.1216 |
| Med. temp         | −33.0323   | 61.1716| −0.54| .590  | −154.1795               | 88.1149 |
| Woody feed        | 19.6269    | 44.7138| 0.44 | .662  | −68.9264                | 108.1803 |
| Straw feed        | −4.9754    | 25.7926| −0.19| .847  | −56.0563                | 46.1055 |
| Shell feed        | −33.0707   | 52.0367| −0.64| .526  | −136.1266               | 69.9853 |
| Non-traditional   | −40.7812   | 62.6608| −0.65| .516  | −164.8777               | 83.3153 |
| Cons.             | 19.6044    | 76.5202| 0.26 | .798  | −131.9399               | 171.1486 |

Note: OLS regression results include indications of coefficient, SE, T, $p > |t|$, and the 95% confidence interval. Sand % and application rate have $p > |t|$ values below 0.05, indicating statistical significance. Detailed STATA input can be referenced in the Supporting Information.
We found soil sand content and biochar application rate to be significantly related to changes in WHC with biochar addition (Table 1). Higher sand content and higher application rates correlated to larger WHC increases.

A Breush–Pagan test conducted in STATA revealed the presence of heteroskedasticity, with a $\chi^2$ value of 42.61. Because this meta-analysis was based on a set of data points from a controlled number of authors, the data are subject to

| Variable       | Coefficient | SE   | T    | $p > |t|$ | 95% confidence interval |
|----------------|-------------|------|------|------|------------------------|
| One-sand %     | –0.1851     | 0.0917 | –2.02 | .046 | –0.3666 – 0.0036       |
| Application rate| 0.5191     | 0.0055 | 93.60 | .000 | 0.5081 – 0.5301       |
| Particle size  | 11.8216     | 4.7970 | 2.46  | .015 | 2.3214 – 21.3218      |
| Low temp       | –6.2110     | 10.9733 | –0.57 | .572 | –27.9431 – 15.5210    |
| Med. temp      | –2.6290     | 12.8996 | –0.20 | .839 | –28.1761 – 4.8163     |
| Woody feed     | –23.2901    | 9.4291 | –2.49 | .014 | –42.1639 – 4.8163     |
| Straw feed     | –10.6080    | 5.4390 | –1.95 | .054 | –21.3798 – 0.1637     |
| Shell feed     | –21.1053    | 10.9733 | –1.92 | .057 | –42.8373 – 0.6267     |
| Non-traditional| –25.8570    | 13.2137 | –1.96 | .053 | –52.0260 – 0.3119     |
| Cons.          | 14.5027     | 16.1363 | 0.90  | .371 | –17.4543 – 46.4598    |

Note: Robust ordinary least squares regression results include indications of coefficient, $SE$, $T$, $p > |t|$, and the 95% confidence interval. One-sand %, application rate, and particle size have $p > |t|$ values below 0.05, indicating statistical significance. Feedstock variables are somewhat significant. Detailed STATA input can be referenced in the Supporting Information.

FIGURE 2 Geographic estimates of potential water holding capacity (WHC) change with biochar. Low, mid-range, and high estimates for WHC change with biochar. The application rates used for the low, mid-range, and high WHC increase estimates are, respectively, 5, 27, and 50 t/ha (37). The particle sizes used for the low, mid-range, and high WHC increase estimates are, respectively, the first quartile, median, and third quartile values from collected data points. The temperature and feedstocks used for each of the three estimates reflect the combinations that produced the lowest, median, and highest WHC changes within our regression (non-traditional feedstock/low temperature for the low estimate, grassy feedstock/medium temperature for the mid-range estimate, and grassy feedstock/high temperature for the high estimate). Coefficients of regression are used for each variable to produce estimates based on U.S. county soil texture (Dieter et al., 2018; ESRI, n.d.; Liu et al., 2013). Detailed GIS input can be found in the Supporting Information.
heteroskedasticity, meaning that the standard errors are biased towards subpopulations and may not reflect normal and constant variance. Thus, to correct for heteroskedasticity we analyzed the data using a robust regression without normal error assumption, which gives appropriate weights in the regression to establish variable significance in the meta-analysis (Table 2).

We found sand content, application rate, particle size and feedstocks to be significantly related to changes in WHC with biochar-amended soil. In addition to sand and application rates, which were also significant from the OLS regression, larger particle sizes were found to result in larger WHC increases. Woody, straw, shell, and non-traditional feedstocks were all found to correlate with smaller WHC increases in comparison with grass feedstock. (Note that the grass feedstock is assumed as the “control” in the regression, so all estimated coefficients on the other feedstocks are relative to grass. This must be done as the feedstock variable is an indicator variable.)

Using these regression estimates, we create a US sensitivity map displaying estimates of WHC increase in response to low, medium, and high range of biochar application rates (Figure 2). This map shows that regions in the U.S. in the Southeast, far North and Northeast, and West, based on their high sand soil content, are likely to see increases in WHC with biochar application.

We also use the average soil texture, application rate, and particle size from our collected studies to explore the expected WHC change with different feedstock and pyrolysis temperature combinations (see Figure 3). The type of feedstock used was found to be somewhat significant according to p-values, as woody (p < .014), straw (p < .054), shell (p < .057), and non-traditional (p < .053) feedstocks were all found to negatively impact WHC in comparison to grassy feedstock. Temperature of pyrolysis was not found to be significant. However, our regression coefficients can be used to acknowledge how different temperature and feedstock pairings may influence soil WHC (Figure 3).

4 | DISCUSSION

Our regression results showed that soils with higher sand content experienced larger increases in WHC with biochar use. This is likely because sandy soils have a lower original WHC, allowing for larger change. It is also likely driven by the size and shape differences between biochar particles and sand particles, allowing for more interpore space creation following biochar amendment.

The biochar application rate was a statistically significant factor affecting the change in WHC, with larger application rates correlating to larger increases in WHC. However, it is important to note that the biochar lab data included here often include much higher application rates than would be economically feasible in the field. Average agricultural application rates range from 5 to 50 t/ha (Major, 2010), while the average application rate in our collected studies was 108.48 t/ha. Of our meta-analysis data, 37.5% were from field studies, while 62.5% of our data were from studies conducted in lab or greenhouse settings. Thus, while our study confirms a relationship between application rate and change in WHC, we do not make recommendations for an optimal application rate to be used in the field based on our analysis.

Particle size was also statistically significant in our data set. Larger biochar particle sizes led to larger increases in WHC. This aligns with previous research (Fischer et al., 2019; Liu et al., 2017; Tanure et al., 2019) that predicts when biochar particles are larger than host soil particles, the biochar will disrupt packing thereby creating more interpore space to hold water. This increase in WHC from interpores is augmented by potential increases in water holding from existing intrapores within the biochar itself (Liu, Dugan, et al., 2016; Liu, Wang, et al., 2016; Liu et al., 2017; Yi et al., 2020).

While our assumption that increases in WHC parallel increases in PAW is supported by literature for sandy soils (Liu et al., 2017), it is not yet possible to similarly generalize about loamy or clay soils. Our data were primarily based on studies in sandy soils, so statements and assumptions of this
work should not be extrapolated to non-sandy soils. Basic research aimed at understanding the physical mechanisms behind biochar’s effect on PAW is necessary to ground broader statements of biochar’s soil water benefits in all soil textural ranges and help support biochar adoption in agriculture.

Biochar is being used and studied for soil organic carbon (SOC) interactions and carbon sequestration, so it is relevant to note that SOC is not used as a variable for consideration in our meta-analysis (Dumortier et al., 2020; Kammann et al., 2017; Windeatt et al., 2014; Woolf et al., 2010). The performance of biochar to increase SOC may depend on nutrients dissolved in soil water, and the levels of dissolved nutrients are influenced by qualities of the biochar that we do use as variables in this study (Majumder et al., 2019). For example, dissolved organic carbon (DOC) which passes through pore spaces is influenced by soil water content; biochar is shown to increase these pore spaces and increase DOC when applied to soil (Liu, Dugan, et al., 2016; Liu, Wang, et al., 2016). Biochar interacts with and alters SOC in sophisticated ways, but we do not show how different SOC and DOC alterations with biochar application affect WHC. Future research would be important to specifically identify and/or quantify the connection between changes in soil water content and SOC with biochar addition.

The variables we include in our meta-analysis reflect soil and production characteristics of biochar that may be realistically available to agricultural stakeholders. Farmers are acutely aware of soil texture and chosen application rates, and are able to measure particle sizes of purchased biochar either on their own accord or provided by the biochar production company. Biochar producers readily advertise feedstock of production (e.g., Wakefield, Vermont Organics Reclamation, Char Bliss). While temperature is not readily advertised, we did not find temperature to be significantly correlated to changes in WHC. Our analysis can thus be used to inform consumers of the factors that should be accounted for when attempting to increase water retention qualities of soil through biochar application.

4.1 Methodology for calculating potential cost savings

With a working assumption that agricultural consumers of biochar are measuring soil water content to estimate need and frequency of irrigation in tensiometric form, irrigation cost savings may derive from reduced frequency and volume as outlined in Equations (1) and (2). Specifically, we posit

\[ C_1 = F_{\text{equip}} + O_{\text{M&L}} + E + W, \]  

where \( C_1 \) is the total cost of irrigation, \( F_{\text{equip}} \) is the fixed cost (including depreciation) of installed equipment, \( O_{\text{M&L}} \) is the cost of field maintenance and labor, \( E \) is the cost of energy for pumping, and \( W \) is the cost of water purchased off-farm.

Increased WHC may result in decreases in variable cost parameters such as \( O_{\text{M&L}}, E, \) and \( W \) due to decreased irrigation need and frequency. Over time, decreased irrigation frequency may also lower \( F_{\text{equip}} \) especially if depreciation of installed equipment occurs more gradually with decreased volumetric usage.

The potential cost savings derive directly from a potential reduction in the irrigated water requirements as a result of biochar application. To begin with, increased WHC will decrease runoff from rainfall, as well as the runoff from irrigated water, which itself is not needed in as significant quantities due to higher WHC. This is described by Equation (2) and in Figure 4. Specifically, we note that the total amount of water needed for healthy crop yield, \( T_S \), can be given as

\[ T_S = V_{\text{IRR}} \theta_{\text{IRR}} \left( 1 + X_B \right) + V_{\text{RAIN}} \theta_{\text{RAIN}} \left( 1 + X_B \right), \]

where \( V_{\text{IRR}} \) and \( V_{\text{RAIN}} \) are the volumes of water from irrigation and rainfall, respectively, and \( \theta_{\text{IRR}} \) and \( \theta_{\text{RAIN}} \) are the fractions of water from irrigation and rainfall, respectively, retained in the soil prior to biochar application. The variable \( X_B \) represents the impact on soil water retention from the application of biochar, so it takes a value of non-zero only post biochar application. Hence, we can find the volumetric requirements for irrigated water as

\[ V_{\text{IRR}} = \frac{T_S - V_{\text{RAIN}} \theta_{\text{RAIN}} \left( 1 + X_B \right)}{\theta_{\text{IRR}} \left( 1 + X_B \right)}. \]

The impact of biochar application for irrigated water volumes is then given as

\[ \frac{\partial V_{\text{IRR}}}{\partial X_B} = \frac{-T_S}{\theta_{\text{IRR}} \left( 1 + X_B \right)^2} < 0, \]

or, as \( X_B \) rises, the volumetric requirement for irrigated water declines.

With biochar addition and subsequent increased WHC, \( T_S \) and \( V_{\text{RAIN}} \) do not change, but more of the rainfall water volumes are retained in the soil, thus changing the \( V_{\text{IRR}} \) requirement. Accordingly, a decrease in \( V_{\text{IRR}} \) will result in decreased costs (Equation 1).

While few sites make publicly available the information needed to calculate potential decreases in irrigation volume, we were able to demonstrate the utility of the framework described here using site data from the University of Nebraska-Lincoln’s Agricultural Water Management Network. Weekly crop evapotranspiration (ET) information is reported through their ETGage data collection program (NAWaN, n.d.a,b). Site Lincoln7 reported 2019 crop water use data and is located in a region of primarily sandy soil.
(Dieter et al., 2018; ESRI, n.d.; Liu et al., 2013). During the first week of July 2019 (07/01/19-07/08/19), ET was estimated to be 1.85 mm/day and rainfall was estimated to be 1.50 mm. In mid-June 2019, USDA reported that 98% of the corn crop in Nebraska had been planted (USDA, 2019). We therefore assume that this crop was in corn growth stage V2 during the first week of July with a water need of 0.185 mm/day (see growth stage definition in NAWMN, n.d.a,b). By converting the 0.185 mm/day requirement into a volume/ hectare, we establish that $T_0$ would equal 34.21 gallons and rainfall of 1.50 mm equal to a volume/hectare of 39.63 gallons ($V_{RAIN}$). To complete this example, we also assume that the loamy sand reported in this section of the county would have a base WHC of 8% (applied to both $\theta_{IRR}$ and $\theta_{RAIN}$) (Weil & Brady, 2006). Using Equation (2), an initial irrigation volume with these variables would be 387.00 gallons/hectare without biochar addition. Using our estimated coefficients from the statistical analysis to determine $X_B$ along with median values of application rate, particle size, and temperature, irrigation volume with biochar ($V_{RAIN}$) could be decreased to 240.74 gallons/hectare, according to Equation (2). This represents a 37.9% decrease in irrigation need from the base estimate without biochar. While we acknowledge that this example contains many assumptions, it shows that by combining an estimate of $X_B$ with Equation (2), agricultural stakeholders can begin to estimate potential irrigated water savings, and thus financial savings, that could be realized through the application of biochar.

This approach to estimating cost savings is conservative because it does not consider the additional improvements that can be realized from decreased plant water stress. Plant stress caused by non-favorable conditions, such as drought, can result in decreased crop yields (Mosa et al., 2017). Increased soil WHC lessens the potential for drought stress, especially during dry conditions where biochar-amended soils may retain more rainfall. Decreasing plant stress conditions can also result in financial benefits through the decreased potential of smaller crop yields and agricultural damage (Crane-Droesch et al., 2013). Healthier crops subjected to lower plant stressors will also be less susceptible to pest vulnerability (Altieri & Nicholls, 2003), which may decrease the necessity of pesticide use, thus decreasing financial and environmental costs (Aktar et al., 2009). Increased crop yield and crop health related to biochar’s soil water retention benefits, along with biochar’s nutrient retention capabilities (Arif et al., 2015), may also decrease the necessity of nitrogen fertilizer use, which introduces an additional cost savings, as well as an important environmental benefit with the reduction of reactive nitrogen runoff (Borchard et al., 2019).

Exact cost savings from biochar use are difficult to estimate because costs associated with irrigation depend on many independent factors, including specific crop water needs, rainfall frequency, pumping height and logistics, water cost and source ownership, and irrigation installation, all of which can vary regionally. Here we provide a framework for individual consideration of biochar cost savings. Decreased irrigation volume and frequency, as well as subsequent crop benefits, provide a basis for the financial analysis of biochar in relation to soil water retention.

More field experimentation involving biochar will also be important in firmly establishing biochar effects on water retention in soils, as well as crop benefits and carbon storage abilities. A great portion of biochar literature is based on laboratory studies which use controlled soil mixtures and conditions that may not accurately indicate the reality of agricultural conditions where biochar would be used. Further field experimentation will strengthen estimation and information for agricultural adoption.

5 | CONCLUSIONS

Our establishment of soil texture as a significant factor in WHC change, and our mapping of this benefit based on US county soil textures, shows that biochar addition may be most beneficial in counties with high sand soil content concentrated in the north, north east, south east, and western United States. Targeting biochar research and policy schemes to support biochar adoption in these regions may be most beneficial for widespread biochar benefit realization. This geographic analysis may also help biochar producers focus their production and distribution to regions where the product would be most favorable.

Our meta-analysis shows that soil and biochar qualities are both important for the realized WHC benefits from biochar soil amendment. The texture of the soil is an important factor; of the sandy soils studied, those with the highest sand content represent the best environment for
biochar application. This conclusion allows us to predict the US regions that may benefit most from biochar use. In addition, particle size and biochar feedstock as well as application rate affect WHC significantly. We also provide a first framework for estimating irrigation cost savings from increased WHC with biochar amendment (see Equations 2 and 3; Figure 4).

Lack of data in clay soils precludes the use of our model in these systems, and points to the need for more research on soil response to biochar amendment. Studies are especially needed that report the full suite of biochar and soil properties (biochar particle size, feedstock, pyrolysis temperature, and application rate; soil texture, and water properties). These data are necessary to better establish mechanisms of improvement in soil water retention attributable to various biochar properties, as well as crop yield increases and carbon storage, and will help to construct more complete cost-benefit analyses of the product that will encourage adoption and support from landowners, extensions, and agricultural policy makers.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available in the supplementary material of this article.

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**SUPPORTING INFORMATION**

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

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