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Publication Date
2023-12-01

DOI
10.1016/j.fcr.2023.109178

Field Crops Research 304 (2023) 109178

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Rehabilitative capacity of amendments to restore maize productivity following artificial topsoil erosion/ deposition

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ARTICLE INFO

Keywords:
Maize
Topsoil depth
Simulated erosion
Soil amendment
Soil restoration

ABSTRACT

Anthropogenic activities leading to erosion-induced topsoil loss still present a pertinent threat to maize (*Zea mays* L.) productivity across the U.S. Corn Belt region. Using soil amendments has been proven effective in reversing the effects caused by erosion-induced topsoil loss and restoring agronomic productivity and yields to pre-eroded conditions. The current study investigated the impact of simulated erosion and repeated amendment application on agronomic productivity and yields over five growing seasons for a 23-year-old experiment at two central Ohio sites (Waterman Farm: WF; Western Station: WS). Simulated erosion/deposition was employed in 1997 to create three incremental topsoil depths (TSD) (20 cm topsoil removed (TSD-0); 0 cm topsoil removed (TSD-1); 20 cm topsoil added (TSD-2). Three soil amendments (inorganic, synthetic N fertilizer (INO); organic, compost manure (MAN); no amendment (CON)) were investigated for their ability to restore productivity in these cropping systems. Greater TSD produced higher germination counts and crop stand and yielded greater canopy cover during the initial five weeks after germination. The MAN amended soils observed higher values for the productivity parameters during the 2016–2020 growing seasons. Grain and biomass yields were 34–51% and 5–12% lower, respectively, for the TSD-0 level and 4–10% and 3–6% greater, respectively, for the TSD-2 level when compared to the undisturbed, TSD-1 level. Relative biomass yield losses (% per cm topsoil depth lost) were 0.921 for the WF site and 0.254 for the WS site, corresponding to average biomass losses (Mg ha^{-1} cm^{-1} yr^{-1}) of 0.083 and 0.026 for each site. Relative grain yield losses (% per cm topsoil depth lost) were 1.29 for the WF site and 0.514 for the WS site, equating to mean grain losses (Mg ha^{-1} cm^{-1} yr^{-1}) of 0.083 and 0.026 for each site. The rehabilitative capacity of the soil amendments followed a trend of INO > MAN at the WF site and MAN > INO > CON at the WS site. The deleterious effects of erosion on grain and biomass yields were found to be reversed with the addition of the INO and MAN amendments at the WS site due to improvements in soil health and SOC pools. The MAN amended soils produced grain and biomass yields that were nearly 2.5% and 5.6% greater than the INO amended soil when compared to the reference treatment (TSD-1-CON). This study demonstrates that sustainable soil management practices coupled with annual soil amendment addition can mitigate the deleterious effects of erosion and rebound maize yields to pre-eroded conditions for soils experiencing severe topsoil loss.

1. Introduction

The global population is expected to increase to 9.7 billion by 2050 and will necessitate greater agronomic yields to achieve food security (United Nations Department of Economics and Social Affairs, 2022). The goal for a food secure future can become severely threatened when soil

Abbreviations: TSD, topsoil depth; WF, Waterman Farm; WS, Western Station; MAN, compost manure; INO, synthetic N fertilizer; CON, unamended control; RCBD, randomized complete block design; HI, harvest index; BMP, best management practices; NPP, net primary productivity.

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https://doi.org/10.1016/j.fcr.2023.109178
Received 20 February 2023; Received in revised form 13 September 2023; Accepted 27 October 2023
Available online 6 November 2023
0378-4290/

management is unsustainable thus hindering soil health and accelerating topsoil loss. Adapting cropping systems now will assist in increasing water and energy efficiencies while at the same time, building soil health, sequestering carbon (C), and increasing yields. Topsoil depth (TSD) is an indirect indicator of both soil health and crop productivity (Izaurralde et al., 2006; Papiernik et al., 2009; Thaler et al., 2021). Soil health is the perpetual capacity of soil to function as a living system to support biological productivity and carry out specific services, including sustaining plant growth (Lal, 2016; Lehmann et al., 2020). A reduction in TSD decreases overall soil health by creating a shallower topsoil horizon that reduces soil productivity and functionality thus jeopardizing the ability to support many soil and plant ecosystem services (Papiernik et al., 2009; Lehmann et al., 2020). Based on the quantity and severity of topsoil loss, crucial soil physical, chemical, and biological properties along with soil C, N, and other fertility pools can become negatively altered (Bakker et al., 2004; Zhou et al., 2015). This creates soil conditions that are not conducive for adequate crop establishment and growth throughout the season and can ultimately hinder crop yields (Papiernik et al., 2009).

Evaluating agronomic productivity in relation to erosion is complex due to the coupling of abiotic, biotic, and soil factors influencing productivity (den Biggelaar et al., 2001; Izaurralde et al., 2006). Growth rates, crop developmental stages, and root structure and density become altered when TSD is decreased, leading to yield reductions (Bakker et al., 2004). When topsoil loss is incremental, yield reductions may go unnoticed until topsoil loss becomes more drastic or crosses a threshold (Larney et al., 2009). These yield reductions can be further masked by technological innovations like improved crop varieties and chemical soil additives (den Biggelaar et al., 2001; Bakker et al., 2004; Izaurralde et al., 2006).

Topsoil removal/addition (or simulated erosion) experiments are a practical, effective approach for quantifying long-term erosion-productivity relationships in agroecosystems (den Biggelaar et al., 2001; Bakker et al., 2004; Larney et al., 2009). This experimental approach simulates different erosion severities through a one-time mechanical removal or addition of topsoil that creates varying TSDs (Dormaar et al., 1997; Larney and Olson, 2018). This allows researchers the ability to study agronomic productivity at contrasting levels of erosion or deposition (Jagadamma et al., 2009; Larney et al., 2016). Simultaneously, simulated erosion experiments allow for the imposition of soil amendments to test their rebounding effects on soil properties and agronomic yields (Larney and Olson, 2018). Erosion-productivity relationships have been studied for a range of crops including maize (*Zea mays*; Gollany et al., 1992; Oyedele and Aina, 2006; Sui et al., 2012, Zhou et al., 2012; Guo et al., 2021), soybean (*Glycine max*; Wang et al., 2009; Liu and Wei, 2014; Gao et al., 2015; Zhou et al., 2015), wheat (*Triticum aestivum*; Larney et al., 1995; Izaurralde et al., 1998; Larney et al., 2008; Allen et al., 2011; Larney and Olson, 2018), and other economically important crops (Carter et al., 1985; Flörchinger et al., 2000; Li et al., 2020).

The sensitivity of maize productivity and yields to erosional processes ranks within the top three of crops, in between soybean and wheat (Zhang et al., 2021). The short-term effects of simulated erosion on maize include declines in grain and above-ground biomass yields with decreasing TSD levels. Changere and Lal (1995) reported a 32% decline in maize yields over a 2-year period when 20 cm of topsoil was removed. Sui et al. (2009) observed 10–13% decreases in maize yields when up to 10 cm of topsoil was removed and 46–73% more losses when up to 30 cm of topsoil was removed. Guo et al. (2020) reported a 9–22% decrease in maize yields for a Mollisol three years after 10 and 20 cm of soil was desurfaced. Topsoil removal/addition methods produce more realistic results when studies are conducted for longer durations (e.g., >10 years) (Bakker et al., 2004; Larney and Olson, 2018). However, the deleterious effects of simulated erosion on maize yields can persist many years after simulated erosion has taken place. Jagadamma et al. (2009) reported maize yields decreased 44% and 60% for an eroded Alfisol in central Ohio (20 cm topsoil removal) 10 years after simulated erosion had occurred. Similarly, in an Alfisol in west-central Ohio, Jagadamma and colleagues observed grain yield decrease by 12% when 20 cm of topsoil was removed compared to when 20 cm of topsoil was added. Liang et al. (2018) reported that grain yield decreased 51% and increased 47% when 20 cm of topsoil was removed and added, respectively, 15 years after simulated erosion had occurred on an Ohio Alfisol. Lindstrom et al. (1986) reported that after 20 years of simulated erosion on a Mollisol with 30 and 45 cm of topsoil removal, maize grain yields were still 20–25% below that of the uneroded control, even though soil properties in the surface soil of the eroded plots had improved. Even with long-term best management practices (BMPs), incremental losses in yields with decreasing topsoil thickness cannot always be restored to pre-eroded conditions, especially when erosional depth is > 20 cm (Larney et al., 2009; Zhang et al., 2021).

Long-term datasets are also useful for testing erosion-productivity following the addition of soil amendments (e.g., chemical fertilizers, manures), but are limited in maize. Application of manure and nitrogen (N) fertilizer produced variable effects on grain and aboveground biomass maize yields after 10 years for an Alfisol in Ohio, with losses being mainly attributed to differences in soil texture between the two sites in Ohio (Jagadamma et al., 2009). After 16 years of cultivation, Larney et al. (2009) reported that wheat yield losses were estimated to range between 50 and 59 kg ha^{-1} cm^{-1} yr^{-1} for two sites in Alberta, Canada. Losses were shown to narrow with the application of both chemical fertilizer and manure, with the manure-amended soils incurring the smallest loss (0.85% cm^{-1} loss for manure amended vs. 1.9% cm^{-1} loss in the unamended soil). Zhou et al. (2015) reported maize yield losses to be 69.1 kg ha^{-1} cm^{-1} yr^{-1} when amended with chemical fertilizer and 48.4 when amended with manure, over a nine-year period. Similarly, soybean yield losses were observed to be 14.0 and 9.1 kg ha^{-1} cm^{-1} yr^{-1} with fertilizer and manure additions, respectively, for the same duration (Zhou et al., 2015). Both aforementioned studies reported that the restorative ability of amendments to rebound yields was greatest at lower TSD levels. Summarized across studies, greater restorative ability of amendments to rebound and restore agronomic yields followed manure>topsoil>chemical fertilizer >irrigation (Larney et al., 2009; Zhou et al., 2015; Zhang et al., 2021). However, there is still much uncertainty around the restorative ability of amendments in maize systems experiencing severe topsoil loss (e.g., ~20 cm), especially pertaining to which types of amendments would serve best to rebound yields, how much yield loss stemming from the erosion can be narrowed after amending, and the amount of time needed for these amended soils to attain yields seen pre-erosion. This study provides updated agronomic findings for two central Ohio sites that have been cropped and maintained since 1997 and last reported by Jagadamma et al. (2009). Furthermore, the study offers (1) new insights into maize productivity and yields after 23 years of long-term, repeated application of organic, inorganic, and no amendment for a silt loam soil commonly used to cultivate maize in the U.S. Midwest, (2) demonstrates updated trends in yield growth/ narrowing of yield loss resulting from improvements in soil properties due to repeated amendment use, and (3) reveals restoration time needed to rebound yields back to pre-eroded soil conditions.

The objective of this study was to assess agronomic productivity using specific indicators on two truncated soils in Central Ohio and evaluate the capacity to restore productivity using varying kinds of soil amendments. Specific objectives for this study included: (1) evaluate the impact of TSD and soil amendments on several biometric crop productivity indicators and maize grain and biomass yields over five growing seasons (2016–2020), (2) determine erosion-productivity-soil amendment relationships over the course of these five growing seasons, and (3) assess whether deleterious effects stemming from erosion can be diminished over time with annual amendment application. We hypothesized that (1) maize biometric productivity indicators and grain and biomass yields will increase with increasing TSD and repeated addition of organic soil amendments, (2) repeated organic soil amendments will rebound yields better under severe TSD depletion and narrow yield gaps between TSD levels, and (3) the deleterious effects from erosion can be diminished with improvements in soil health stemming from repeated amendment addition.

2. Materials and Methods

2.1. Study areas

This study was conducted on long-term field plots at two Ohio State University research stations in Central Ohio – (1) The Waterman Agricultural and Natural Resources Laboratory (Waterman Farm; WF) in Columbus, Ohio (40°00'38.0"N, 83°02'24.2"W) and (2) Western Agricultural Research Station (Western Station; WS) near South Charleston, Ohio (39°51'46.0"N, 83°40'20.8"W) (Fig. 1 A). Field plots at WF and WS were established in 1997 and have been continuously maintained and cultivated since. Soils at WF are classified under the Crosby soil series (fine, mixed, active, mesic Aeric Epiaqualfs) (WRB Classification: Stagnosol). These soils are deep, have a silt loam textured surface horizon, are somewhat poorly drained, located on a 2–6% slope, and derived from glacial till parent material (Soil Survey Staff, 2020). Soils at WS are classified as a Strawn-Crosby complex (Fine-loamy, mixed, active, mesic Typic Hapludalfs) (WRB Classification: Luvisol). These soils are deep, have a silt loam textured surface horizon, are well-drained, located on a 0–2% slope, and derived from glacial till parent material (Soil Survey Staff, 2020). The mean annual rainfall and temperature for the region in central Ohio (WF site) are 1056 mm and 11.9 °C, respectively (National Oceanic and Atmospheric Administration, 2020). The mean annual precipitation and temperature for the region in west-central Ohio (WS Site) are 1022 mm and 10.7 °C, respectively (National Oceanic and Atmospheric Administration, 2020). Monthly precipitation for the 2016–2020 growing seasons for both sites can be found in Fig. 1B. A summary of key soil characteristics for each site can be found in Tables S1 and S2, respectively.

2.2. Experimental design

This study was conducted using long-term simulated erosion/amendment plots at WF and WS but focused specifically on the growing seasons between 2016 and 2020. Treatments at each site comprised three topsoil depth (TSD) levels and two/three soil amendments. The TSD levels were created at the start of the experiments in 1997 through the removal and addition of surface soil. TSD levels included (1) removal of 20 cm of soil (eroded; TSD-0), (2) undisturbed soil (uneroded; TSD-1), and (3) addition of 20 cm of soil (deposition; TSD-2). Amendments applied for these studies were (1) organic compost manure (organic; MAN) and (2) synthetic N fertilizer (inorganic; INO). For the experiment at WS, an additional unamended soil treatment group (control; CON) was included. For the MAN application, dry compost manure (20 Mg ha^{-1} equivalent to 168 kg N ha^{-1}) was top-dressed annually before planting. A summary of the C and N composition of the compost manure can be found in Table S3. For the INO application, urea (46% N) was side-dressed on the soil surface at a rate of 168 kg N ha^{-1}. Urea was applied during the V3-V4 maize growth stage. Selection of these amendments was made based on their common use as fertilizers in Ohio maize cropping systems, and in the case of the compost manure, their abundant availability across the north-central region of the state. Additional experimental site details for the WF and WS sites can be

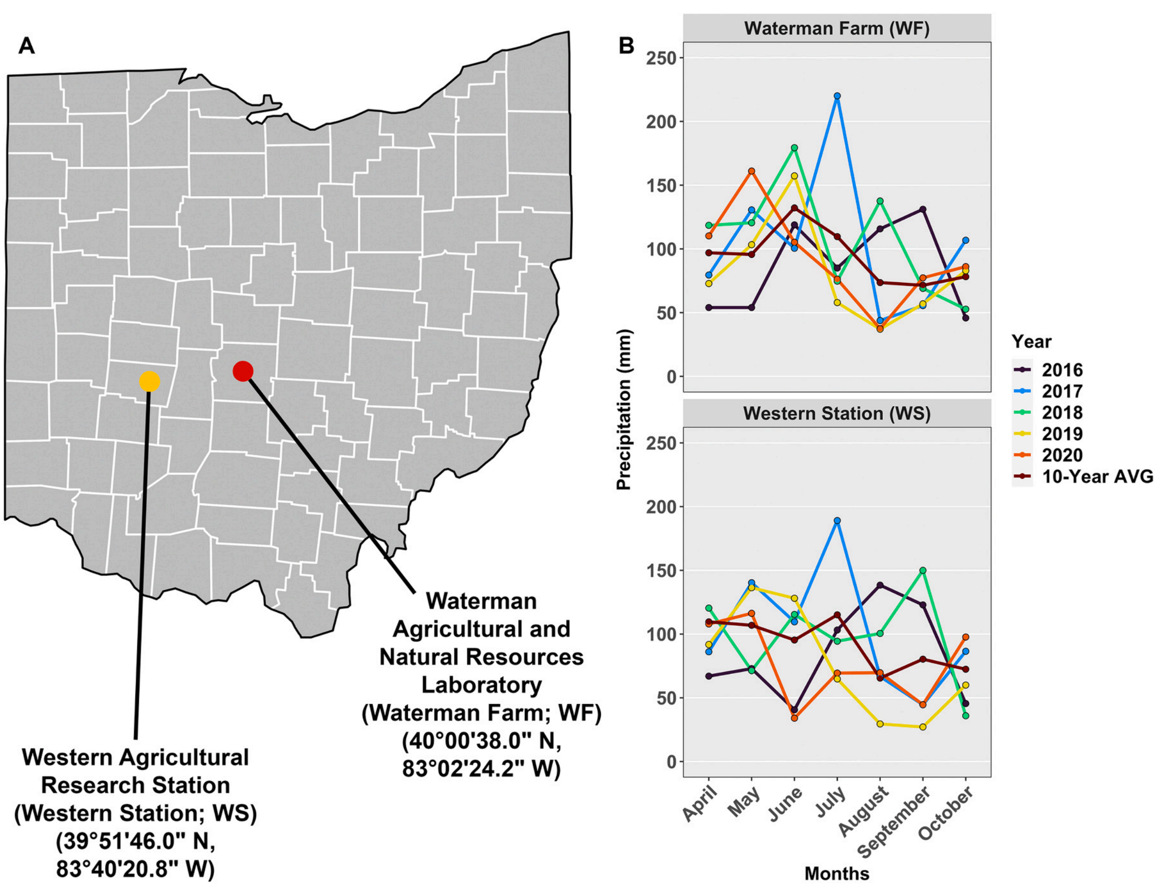

Fig. 1. (A) Field site locations for this study. The red point depicts the Waterman Farm site in Columbus, Ohio (Franklin County). The yellow point depicts the Western Station site near South Charleston, Ohio (Clark County). (B) Growing season monthly precipitation for the Waterman Farm (top) and Western Station (bottom) sites for the 2016–2020 growing seasons. A 10-year average for growing season monthly precipitation is also plotted for comparison for each site.

found in Tables S4 and S5, respectively.

The experimental arrangement at WF was a strip-plot arrangement within a random complete block design (RCBD). TSD was used as the main plot while amendment type was used as the subplot. There was an inadequate level of replication for TSD since treatments were blocked together resulting in pseudoreplication of amendments in each TSD treatment. The experiment at WS was arranged as a two-factor factorial RCBD with three TSD levels and three amendments. Treatments at both sites were replicated in triplicate.

2.3. Biometric maize productivity parameters

Germination (%) was measured 10 days after planting by calculating the total number of seeds that germinated as a proportion of the total number of seeds planted within a 1-m^2 area. Crop stand was measured 21 days after planting by recording the number of plants present within a 1-m^2 area of the plot. Each of these parameters was measured in triplicate. Canopy cover was estimated using digital photography (Nielsen et al., 2012). Measurements began seven days after germination and were recorded on a weekly basis for 5 weeks. A Canon 7D Mark II camera and Apple iPhone 6 S camera were used to capture photographs in 3 different locations within each plot. Photographs were taken when the camera was level with the horizon at arm's length and analyzed using the Canopeo app (Patrignani and Ochsner, 2015). Green vegetation was transformed to white while other background elements were transformed to black. The canopy cover (%) was calculated using the ratio of the white area in the photograph to the overall area of the photograph.

2.4. Maize grain and biomass yields

Grain and aboveground biomass yields were measured within a 1-m^2 area of the two center rows for each plot. Plants were harvested at the R6 physiological maturity growth stage by clipping the base of the plant near the soil surface. Total aboveground biomass, aboveground component minus grain, and grain component masses were recorded. Biomass and grains were each placed in paper bags and oven-dried at 60 °C. A grain moisture meter (Dickey-John Mini-Gac) was used to determine the moisture content of the grain. Dry weights for biomass and grains were adjusted to 15.5% moisture content. The harvest index (HI) was calculated as a ratio of grain yield to that of overall yield (grain+biomass).

2.5. Soil organic carbon (SOC) pools and the soil health index (SHI)

In brief, SOC pools were calculated using the fixed depth method using the bulk soil SOC concentrations and field bulk density (Dheri et al., 2022). The SHI was calculated through a scoring function analysis framework using 12 soil health indicators (Nakajima et al., 2015). Results from both parameters can be found in Moonilall (2022).

2.6. Statistical analysis

Statistical analysis was performed using RStudio, version 4.0.2 (RStudio Team, 2020). A two-way analysis of variance was used separately for each field site, where the biometric productivity parameters and grain and biomass yields were dependent variables, TSD level and amendment type were fixed effects, and replication (block) was a random effect. The effects of TSD, amendment type, and their interaction were investigated using the *agricolae* and *emmeans* packages within RStudio (de Mendiburu, 2021; Lenth, 2023). A post hoc comparison using the Fisher-Least Significant Difference (LSD) test was performed when there was an indication of significant differences at $p < 0.05$ for each response variable. All graphical figures were created using the *ggplot2* package within RStudio (Wickham, 2016). A simple Pearson's correlation test was performed within RStudio using the *corrplot* package to investigate the influence of soil health, agronomic productivity parameters, and agronomic yields as influenced by TSD level and amendment type at the surface 40 cm soil profile (Wei and Simko, 2021). Linear regression models were developed using the *lm()* command with relative yields as the response variable and TSD as the predictor variable. Coefficients for slope and intercept were then extracted.

3. Results

3.1. Biometric productivity measurements

3.1.1. Germination and Crop Stand

At the WF site, TSD level and amendment type did not exert a significant impact on germination and resulting crop stand across each of the four seasons spanning 2017–2020 (Table S3). The 4-year pooled averages for the WF site show that germination ($p = 0.19$) and crop stand ($p = 0.19$) for the TSD-0 level were generally lower than those observed in the TSD-1 and TSD-2 levels, although they did not vary statistically across the 2017–2020 growing seasons (Fig. 2A panel and 2B panel). The 4-year average showed that both germination and crop stand in the TSD-0 level were about 46% lower than in the TSD-1 and TSD-2 levels. Average germination and crop stand for the 4-year period were found to vary significantly between amendment types for this site, where the MAN amended soils had a 3.6% greater germination ($p = 0.04$) and 3.8% higher crop stand ($p = 0.04$) than the INO amended soils (Figs. 2A and 2B panels). The TSD x amendment interaction at this field site was not statistically significant for germination percentage ($p = 0.19$) or crop stand ($p = 0.18$).

For the WS site, the TSD x amendment interaction effect was statistically significant for germination and crop stand for each of the four seasons spanning 2017–2020 (Table S4) as well as across the pooled 4-year averages ($p < 0.001$ for both) (Figs. 2C and 2D panels). During the 2017–2019 seasons, germination was significantly lower in the TSD-0-CON treatment (53.7%) than in all other treatments (87–96%). Similar observations were noted for crop stand during this duration where the TSD-0-CON treatment had a mean stand (7.52 plants m^{-1}) that was significantly lower than all other treatment combinations (12.4–13.7 plants m^{-1}). In 2020, the TSD-1-MAN and TSD-2-MAN had germination (99.2%) that was significantly higher than that of the TSD-0-CON (55.6%) and TSD-0-INO (89.7%) treatments. For 2020, the TSD-0-CON (7.78 plants m^{-1}) and TSD-0-INO (12.6 plants m^{-1}) observed significantly lower crop stands than that of both the TSD-1-MAN and TSD-2-MAN (13.9 plants m^{-1}) treatments. The pooled 4-year averages showed that germination for TSD-0-CON treatment (54.2%) was significantly lower than any other treatment combination (87.9–97.1%). Additionally, the TSD-0-CON treatment also had the lowest crop stand (7.58 plants m^{-1}) compared to all other treatment combinations (12.4–13.8 plants m^{-1}). Those TSD levels amended with MAN tended to have greater germination and crop stands followed by TSD levels amended with INO and CON, respectively.

3.1.2. Canopy cover

Canopy cover was measured weekly for 5 weeks after germination had occurred (Fig. 3). Across week 1 and week 2 measurements, canopy cover did not vary statistically among TSD levels at the WF site (Fig. 3A). At the onset of week 3, a trend began to develop where greater canopy cover was seen with increasing TSD. Week 3 measurements observed differences among TSD levels only during the 2017 and 2020 seasons (Fig. 3A). For both seasons, the TSD-0 level yielded the lowest canopy cover, with 50% less cover recorded in 2017 and 24% less for 2019, compared to the other TSD levels. Week 4 measurements observed strong significant differences for the 2017–2020 seasons (Fig. 3A). Canopy cover for the TSD-0 level ranged 25-75% lower than the other TSD levels. In the 2017 and 2020 seasons, the canopy cover for the TSD-2 treatment was higher than the TSD-1, although they did not statistically differ from one another. The opposite trend was observed for the

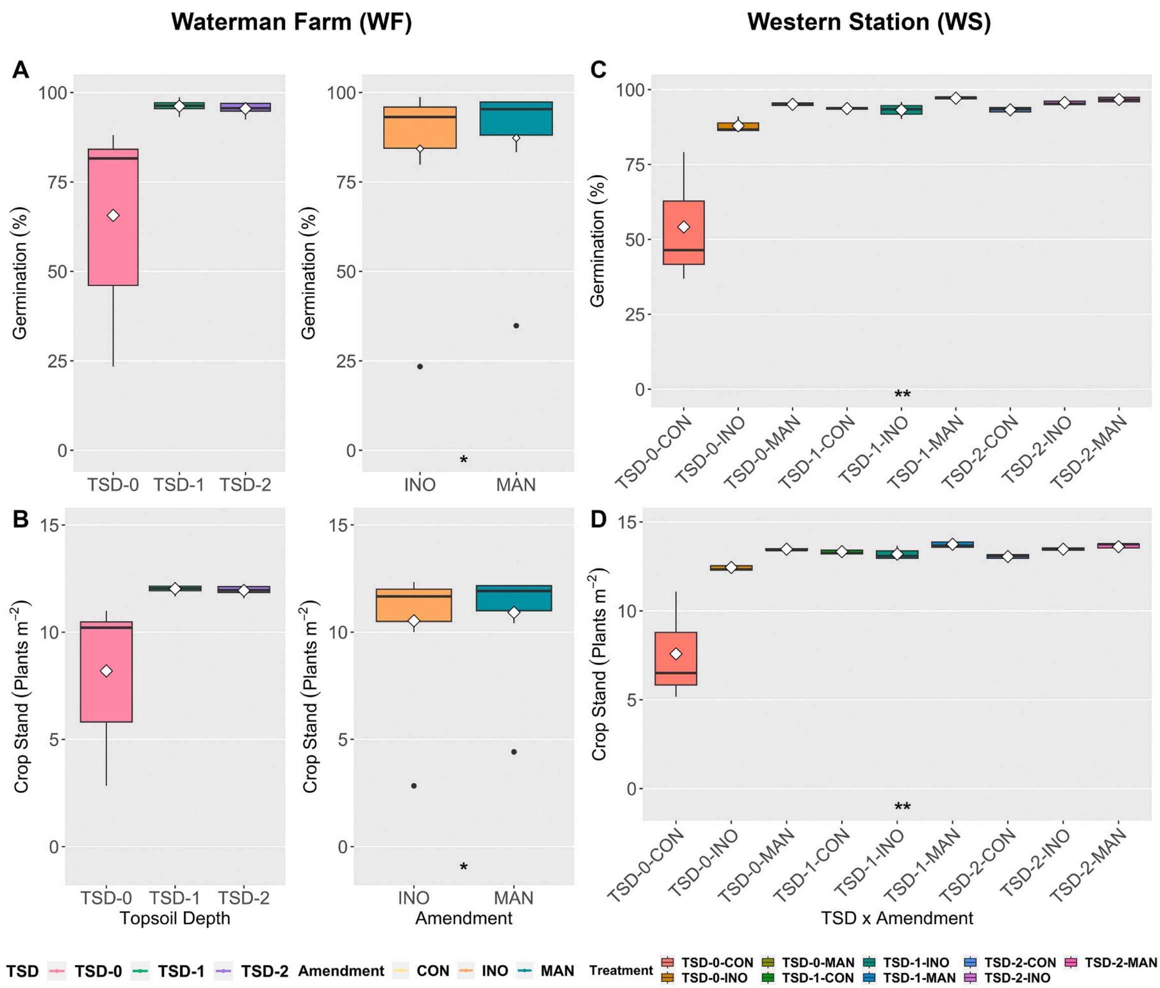

Fig. 2. Five-year average of germination (%) and crop stand (plants m^{-2}) as influenced by topsoil depth (TSD) (left) and amendment type (right) at the Waterman Farm (WF; A,B). TSD x amendment interaction effects are presented for germination and crop stand at the Western Station (WS; C,D) site. The white diamond within the boxplot represents the mean value. * and * * correspond to p-values of < 0.05 and < 0.01, respectively. TSD = topsoil depth, TSD-0 = 20 cm of topsoil removal, TSD-1 = no topsoil removal, TSD-2 = 20 cm of topsoil added, CON = control (no amendment), INO = inorganic fertilizer, MAN = organic fertilizer.

2018 and 2019 seasons, where the TSD-1 level yielded the highest canopy cover at this measurement time point. Week 5 measurements observed that TSD exerted a significant effect on canopy cover (Fig. 3A) where the TSD-0 level observed on average 36–61% lower cover than the TSD-1 and TSD-2 levels. The observations seen between the TSD-1 and TSD-2 levels during the week 4 measurement remained apparent during the week 5 measurement.

Week 1 canopy cover measurements did not vary between amendments during the four growing seasons at the WF site (Fig. 3B). Week 2 measurements only observed measurable differences during the 2018 season where the MAN amended soil produced a significantly higher canopy cover than the INO amended soil (Fig. 3B). Week 3 measurements observed significantly different canopy cover values across amendments between the 2018–2020 seasons (Fig. 3B). Canopy cover for the soils amended with MAN was about 15–27% greater than the soils amended with INO over these three years. Similar results were noted for the week 4 measurements, where the MAN amended soil produced cover that was on average 20–25% greater than that of the soils amended with INO during these three growing seasons. During week 5 measurements, the gap in canopy cover was narrowed during the week 5 measurements resulting in no significant differences in canopy cover for any of the four growing seasons (Fig. 3B). Generally, the MAN amended soils still maintained a greater canopy cover than the INO amended soils.

The pooled 4-year weekly canopy cover percentages for the WF site are reported in Figs. 3A and 3B. During week 1 and week 2 measurements, canopy cover did not observe significant differences among the TSD levels or amendments. In week 3 measurements notable differences were observed for amendment type, but not for TSD. The MAN amended soil had a canopy cover that was 19% greater than that of the INO amended soil. In week 4, canopy cover observed significant differences for both TSD levels and amendment type. The canopy cover for the TSD-1 and TSD-2 levels was 43% greater than the TSD-0 level. Soils that were amended with MAN produced canopy cover percentages that were 20% greater than those soils amended with INO. Week 5 measurements demonstrated significant differences among TSD levels, but not amendment type. The TSD-1 and TSD-2 levels had canopy cover that was 48% greater than the TSD-2 level. The TSD x amendment interaction for this field site was not significant for any of the weekly canopy cover measurements.

At the WS site, canopy cover was measured across three seasons between 2017 and 2020, with the exception being in 2018. Across week 1 and week 2 measurements, canopy cover did not significantly differ among TSD levels (Fig. 3C). Starting in week 3, canopy cover differed significantly across TSD levels during the 2017 and 2020 seasons (Fig. 3C). The canopy cover for the TSD-0 level was about 22% lower than that of the TSD-1 and TSD-2 levels. Week 4 measurements observed TSD levels exerting significant influence on canopy cover during the 2017 and 2019 seasons and observed the TSD-0 level having about 16–17% lower canopy cover than the other TSD treatments (Fig. 3C).

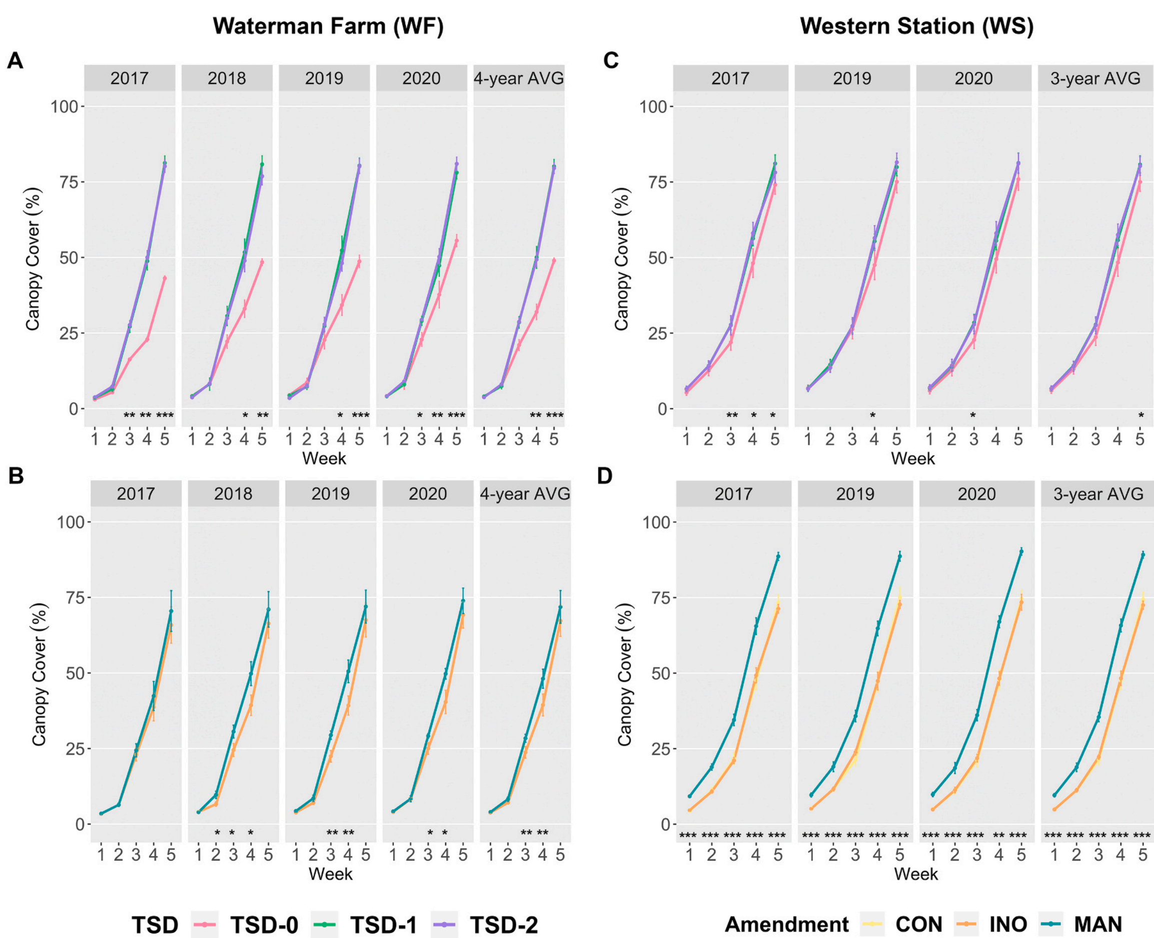

Fig. 3. Canopy cover (%) as influenced by topsoil depth (TSD) and amendment type at the Waterman Farm (WF; A,B) and Western Station (WS; C,D) sites. * , * *, and * ** correspond to p-values of < 0.05, < 0.01, and < 0.001, respectively. AVG = average, TSD = topsoil depth, TSD-0 = 20 cm of topsoil removal, TSD-1 = no topsoil removal, TSD-2 = 20 cm of topsoil added, CON = control (no amendment), INO = inorganic fertilizer, MAN = organic fertilizer.

For week 5 measurements, canopy cover differed across TSD levels only in the 2017 season (Fig. 3C) and observed the greatest canopy cover in the TSD-1 level and lowest in the TSD-0 level. At this time point, the TSD-1 level generated slightly higher canopy cover in two of the three growing seasons.

Canopy cover observed strong differences among amendments for each weekly measurement for all three seasons at the WS site. In every instance, the MAN amended soils yielded greater canopy cover than the CON and INO amended soils. The canopy cover for the MAN amended soils were observed to be 61–68% greater during week 1, 48–53% higher during week 2, 45–51% greater during week 3, 30–33% higher during week 4, and 18–20% greater during week 5 (Fig. 3D). Noteworthy to mention is the fact that the INO amended soil had canopy cover values that resembled values seen in the CON soil, indicating that the MAN amendment had a stronger effect on this variable at this field site.

The pooled 4-year weekly canopy cover percentages for the WS site are reported in Figs. 3B and 3D. At the WS site, canopy cover was found to not differ among TSD levels for the first three weekly measurements. However, strong differences among amendment type were observed. During the first three weeks, it was observed that canopy cover for the MAN amended soil was significantly greater than the CON and INO amended soils. Canopy cover observed significant differences in both TSD levels and amendment type during week 4 and 5 measurements. At these time points, the canopy cover for the TSD-1 and TSD-2 levels was significantly higher than the TSD-0. Additionally, it was observed that canopy cover percentages for the MAN amended soil were maintained greater than both the CON and INO amended soils. The TSD x amendment interaction for this field site was not significant for any of the weekly canopy cover measurements.

3.2. Yields

3.2.1. Grain yield

Grain yield at the WF site differed significantly among TSD levels during the 2018, 2019, and 2020 growing seasons (Fig. 4A). Grain yield for the TSD-0 level was 84–85% lower than both the TSD-1 and TSD-2 levels during 2018 and 2019 and 39–50% lower during the 2020 season. Grain yield differed significantly between amendments only during the 2019 growing season (Fig. 5A). The yield for the INO amended soil was about 36% greater than that of the MAN amended soil. The pooled 5-year grain yield average for the WF site showed that the TSD-1 and TSD-2 levels had yields that were 105–125% greater than that of the TSD-0 level ($p = 0.003$; Fig. 4A). The poor yields observed in the TSD-0 level can be attributed to poor germination and crop establishment and productivity throughout the growing season. The pooled 5-year grain yield average also differed by amendment type, where the INO amended soils had a 16% greater yield than the MAN amended soil ($p = 0.003$; Fig. 5A). The TSD x amendment interaction was not statistically significant for the five-year pooled average ($p = 0.255$).

Maize grain yield at the WS site differed significantly during the 2017, 2019, and 2020 growing seasons (Fig. 4D). In 2017, the TSD-2 level (14.7 Mg ha^{-1}) had a greater yield than both the TSD-0 and TSD-1 (12.8 Mg ha^{-1}) levels. In both 2019 and 2020, the TSD-0 treatment had a 21–22% lower yield than the TSD-1 and TSD-2 levels. Regardless of the year, either the TSD-1 or TSD-2 level had the highest grain yield among TSD. Grain yield differed significantly among

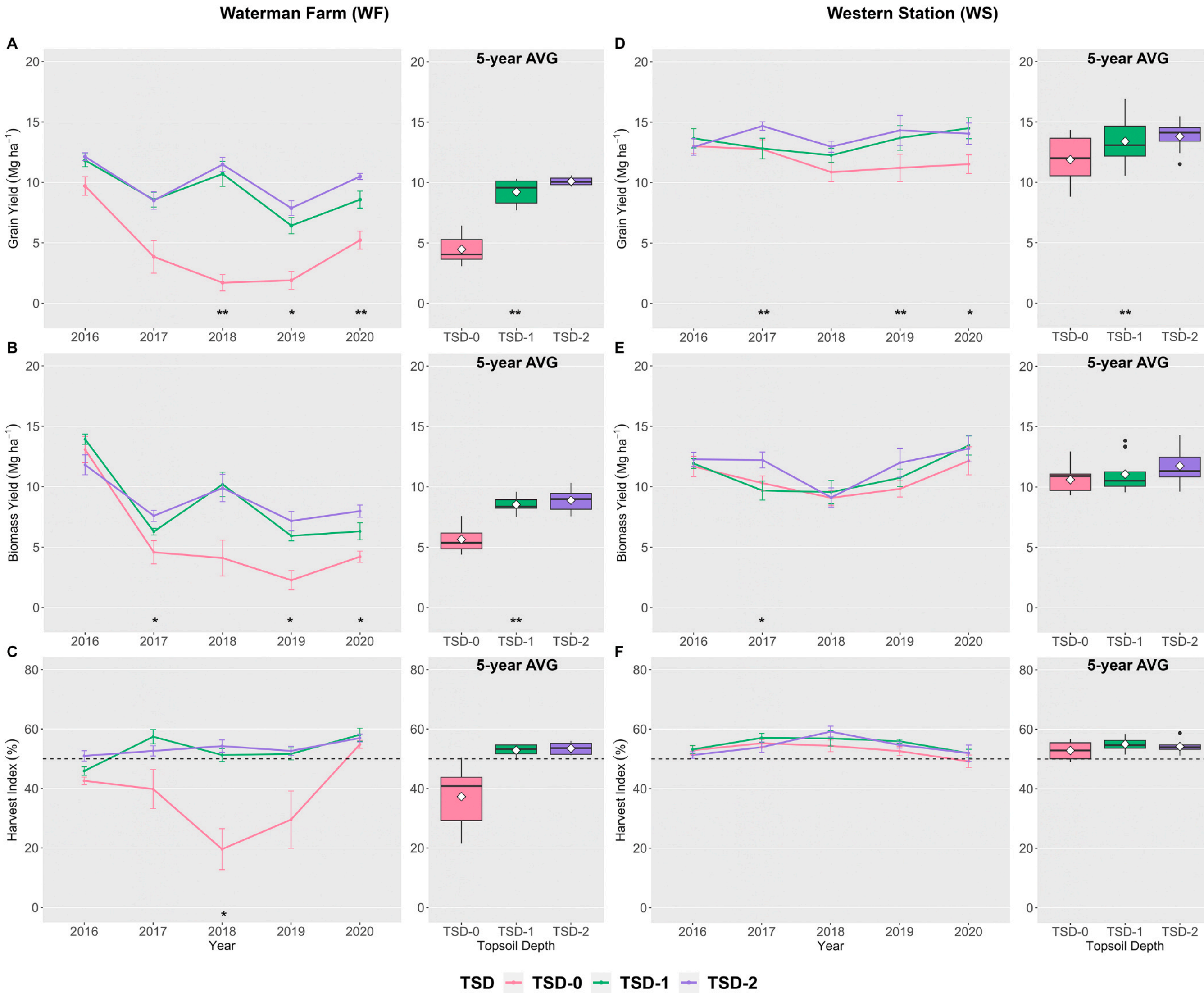

Fig. 4. Grain yield (Mg ha^{-1}), biomass yield (Mg ha^{-1}), and harvest index (%) as influenced by topsoil depth (TSD) at the Waterman Farm (WF; A,B,C) and Western Station (WS; D,E,F) sites. The white diamond within the boxplot represents the mean value. * and * * correspond to p-values of < 0.05 and < 0.01, respectively. The dashed line represents 50% harvest index. AVG = average, TSD = topsoil depth, TSD-0 = 20 cm of topsoil removal, TSD-1 = no topsoil removal, TSD-2 = 20 cm of topsoil added.

amendment type only during the 2017 and 2019 growing seasons (Fig. 5D). In 2017, the MAN treatment produced the greatest yields (15.0 Mg ha^{-1}) followed by the INO treatment (13.3 Mg ha^{-1}), and the CON treatment (12 Mg ha^{-1}). In 2019, the yield for the CON soil was about 24% lower than the yields for the amended soils. Grain yield was always the smallest for the CON treatment and usually greatest for the MAN treatment. The 5-year pooled data for grain yield at the WS site observed strong differences among TSD levels ($p = 0.001$; Fig. 4D) and amendment type ($p = 0.001$; Fig. 5D). Grain yield was observed to increase with increasing TSD and showed that the yields for the TSD-1 and TSD-2 levels were 13% greater than that of the TSD-0 level. Both amended soils had yields that were 13% greater than the CON soil. The TSD x amendment interaction was not statistically significant for the five-year pooled average ($p = 0.104$).

3.2.2. Biomass yield

Biomass yield at the WF site varied significantly among TSD levels during the 2017, 2019, and 2020 growing seasons (Fig. 4B). For these three seasons, greater biomass yields were observed with increasing TSD - greatest for the TSD-2 level, intermediate for the TSD-1 level, and lowest for the TSD-0 level. Biomass yield was significantly influenced by amendment type only during the 2018 and 2019 growing seasons (Fig. 5B). The INO amended soils generated 38% and 35% greater yields than MAN amended soils, respectively, during these seasons. The 5-year pooled biomass yield average at the WF site observed a trend of increasing biomass yield with increasing TSD (Fig. 4B). The yield of the TSD-0 level was about 43% smaller than the yields for both the TSD-1 and TSD-2 levels ($p = 0.007$). Biomass yields did not statistically differ among amendment type ($p = 0.067$), although yields for INO amended soil were slightly greater than those for MAN amended soil. The TSD x amendment interaction was not statistically significant for the five-year pooled average ($p = 0.981$).

Biomass yield at the WS site displayed significant differences among TSD levels only during the 2017 growing season (Fig. 4E). The TSD-2 treatment produced yields that were 22% greater than both the TSD-0 and TSD-1 levels. Biomass yields were significantly influenced by amendment type during the 2017–2019 seasons (Fig. 5E). The MAN amended soil produced the greatest yield over the three-season period. On average, biomass yields for the MAN amended soil were 25% and 28% greater than the other amendments for the 2017 and 2018 seasons,

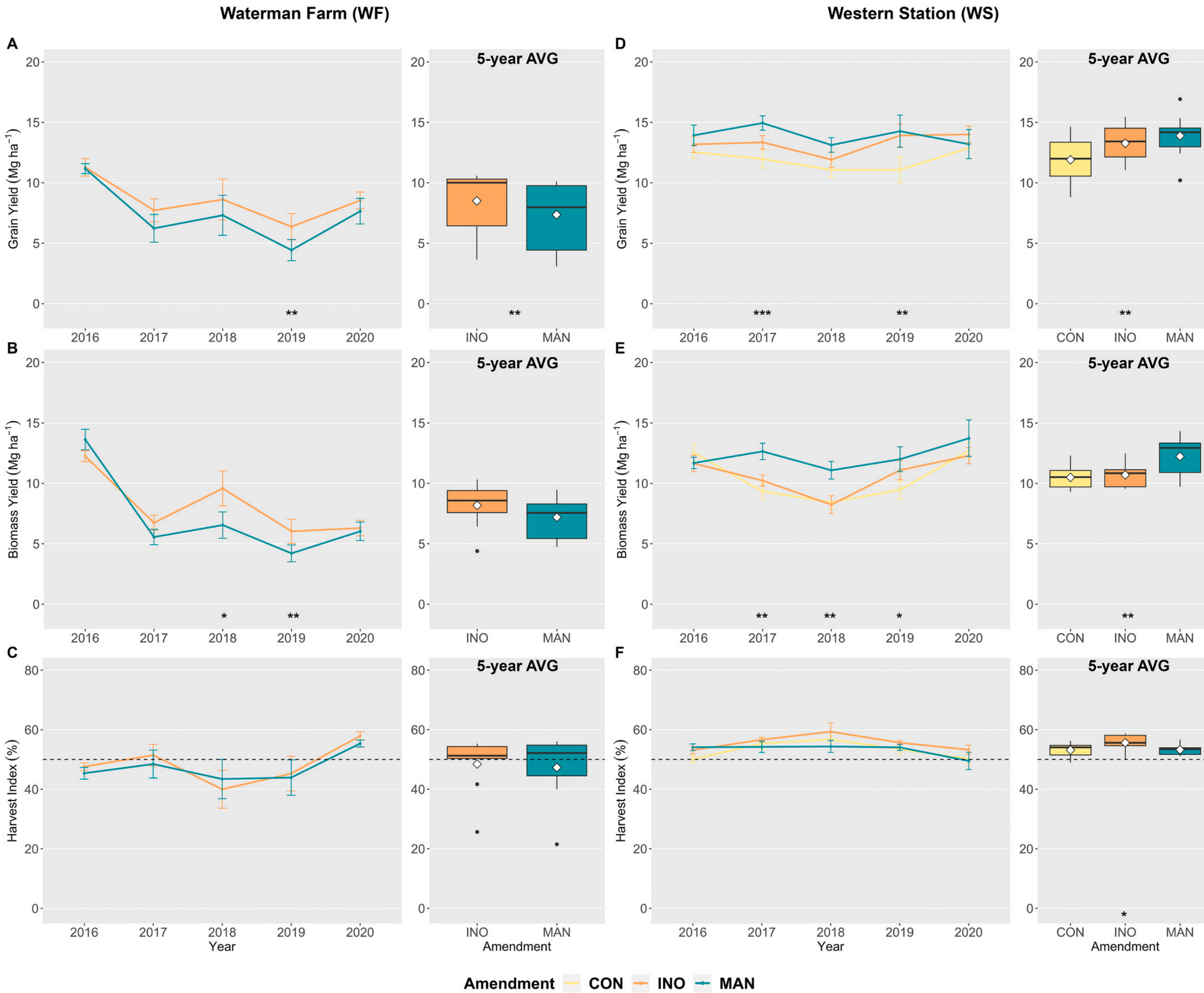

Fig. 5. Grain yield (Mg ha^{-1}), biomass yield (Mg ha^{-1}), and harvest index (%) as influenced by amendment type at the Waterman Farm (WF; A,B,C) and Western Station (WS; D,E,F) sites. The white diamond within the boxplot represents the mean value. * , * *, and * ** correspond to p-values of < 0.05, < 0.01, and < 0.001, respectively. The dashed line represents 50% harvest index. AVG = average, CON = control (no amendment), INO = inorganic fertilizer, MAN = organic fertilizer.

respectively. Yields for the MAN amended soil were significantly greater than the CON soil during the 2019 season. The pooled 5-year biomass yield at the WS site did not vary among TSD levels ($p = 0.088$; Fig. 4E). Generally, yields (Mg ha^{-1}) were highest for the TSD-2 level (11.8), intermediate for the TSD-1 level (11.1), and lowest for the TSD-0 level (10.6). Among amendment types, the yield was about 15% greater for the MAN amended soils than the CON and INO amended soils ($p = 0.005$; Fig. 5E). The TSD x amendment interaction was not statistically significant for the five-year pooled average ($p = 0.461$).

3.2.3. Harvest index

Harvest index at the WF site varied significantly among TSD only for the 2018 season (Fig. 4C). In 2018, the HI for the TSD-0 treatment (19.6%) was significantly smaller than that of the TSD-1 and TSD-2 treatments (51.3–54.3%). Similar observations were noted for all other seasons, although no significant differences among treatments were observed. Amendment type did not have any influence on HI for any of the growing seasons over the 5-year period (Fig. 5C). Since HI is determined from grain and biomass yields, the INO amendment produced a greater HI over the MAN for four of the five seasons analyzed. The pooled 5-year averages for HI at the WF site did not vary significantly for TSD ($p = 0.097$), amendment ($p = 0.286$), or the TSD x amendment interaction ($p = 0.130$) (Fig. 4C). In general, the TSD-0 level produced a HI below 50% signaling that more energy went into producing biomass and not grain. Both TSD-1 and TSD-2 treatments produced HI values that were above 50% showing that grain yields were the majority in the overall harvest. Across amendments, the INO amended soils had a HI that was slightly higher than that of the MAN amended soil.

Harvest index at the WS site was not influenced by TSD (Fig. 4F) or amendment type (Fig. 5F) for any of the five growing seasons. The pooled 5-year HI average did not vary significantly among TSD levels ($p = 0.132$; Fig. 4F). In general, the TSD-1 level had the greatest HI (55%) followed by TSD-2 (54.2%) and TSD-0 (52.9%) levels. Harvest index differed significantly among amendments for the five-year average ($p = 0.045$). The HI for the INO amended soil was about 5% higher than that of the CON and MAN amended soils. The TSD x amendment interaction was not statistically significant for the five-year pooled average ($p = 0.463$).

3.3. Average yield effects and critical thresholds for grain and biomass yields between the 2016–2020 growing seasons

Regression models were developed and evaluated for the pooled five-year averages (representing years 19–23 of the experiment) for grain and biomass yields at both sites (Fig. 6). Both yields were compared against a reference, undisturbed soil that has not experienced any erosion. For the WS site, the TSD-1-CON plot was used as the reference point. However, at the WF site, the TSD-1-INO plot served as the reference since this experimental setup lacked a proper control plot specific to amendment type. The TSD-1-INO, in this case, represents a typical scenario that is practiced in the central Ohio region. Therefore, the yield relationships presented in this section are of relation to the reference treatment (yield, % of reference treatment).

For this five-year study period, critical threshold values for grain and biomass yield (% decline per cm of topsoil depth lost) varied between field sites. At the WF site, grain yield decreased 1.54% cm^{-1} for the INO treatment and 1.29% cm^{-1} for the MAN treatment (Fig. 6A). Biomass yield declined 0.921% cm^{-1} for the INO treatment and 0.888% cm^{-1} for the MAN treatment (Fig. 6B). At the WS site, grain yield decreased 0.514% cm^{-1} for the unamended soil, 0.453% cm^{-1} for the INO treatment, and 0.229% cm^{-1} for the MAN treatment (Fig. 6C). Biomass yield for the unamended soil fell 0.254% cm^{-1} depth, while the INO and MAN amended soils decreased 0.212% cm^{-1} and 0.359% cm^{-1}, respectively (Fig. 6D). The slopes generated in the regression equations for biomass yields were smaller than those for grain yields, demonstrating that amendment type had a greater impact on grain yields than biomass yields. The only exception to this was at the WS site, where the slope for the grain yield for the MAN amended soil was smaller than the slope for biomass yield, indicating that in this case, biomass yields were more sensitive to amendment type. Across field sites, slopes for grain and biomass yields were smaller at the WS site than at the WF site.

Regression models from Fig. 6 were used to estimate mean gains or losses incurred for grain and biomass yields at each field site according

Table 1
Average relative maize grain and biomass losses (or gains represented by a negative value) for varying topsoil depths and amendments for Waterman Farm (WF) and Western Station (WS) sites between 2016 and 2020.

Topsoil Depth (TSD) Levels[1]	Amendment[2]	Waterman Farm (WF)		Western Station (WS)	
		Grain	Biomass	Grain	Biomass
TSD-2	CON	-	-	-10.1	-6.27
	INO	-11.3	-9.60	-19.4	-25.1
	MAN	-4.71	2.03	-19.2	-7.40
TSD-1	CON	-	-	0.167	1.19
	INO	14.5	8.81	-10.3	-3.16
	MAN	26.0	19.8	-14.6	-17.9
TSD-0	CON	-	-	10.4	3.90
	INO	40.3	27.2	-1.25	1.08
	MAN	56.7	37.5	-10.0	-10.7

[1] TSD = topsoil depth, TSD-0 = 20 cm of topsoil removal, TSD-1 = no topsoil removal, TSD-2 = 20 cm of topsoil added.
[2] CON = control (no amendment), INO = inorganic fertilizer, MAN = organic fertilizer.

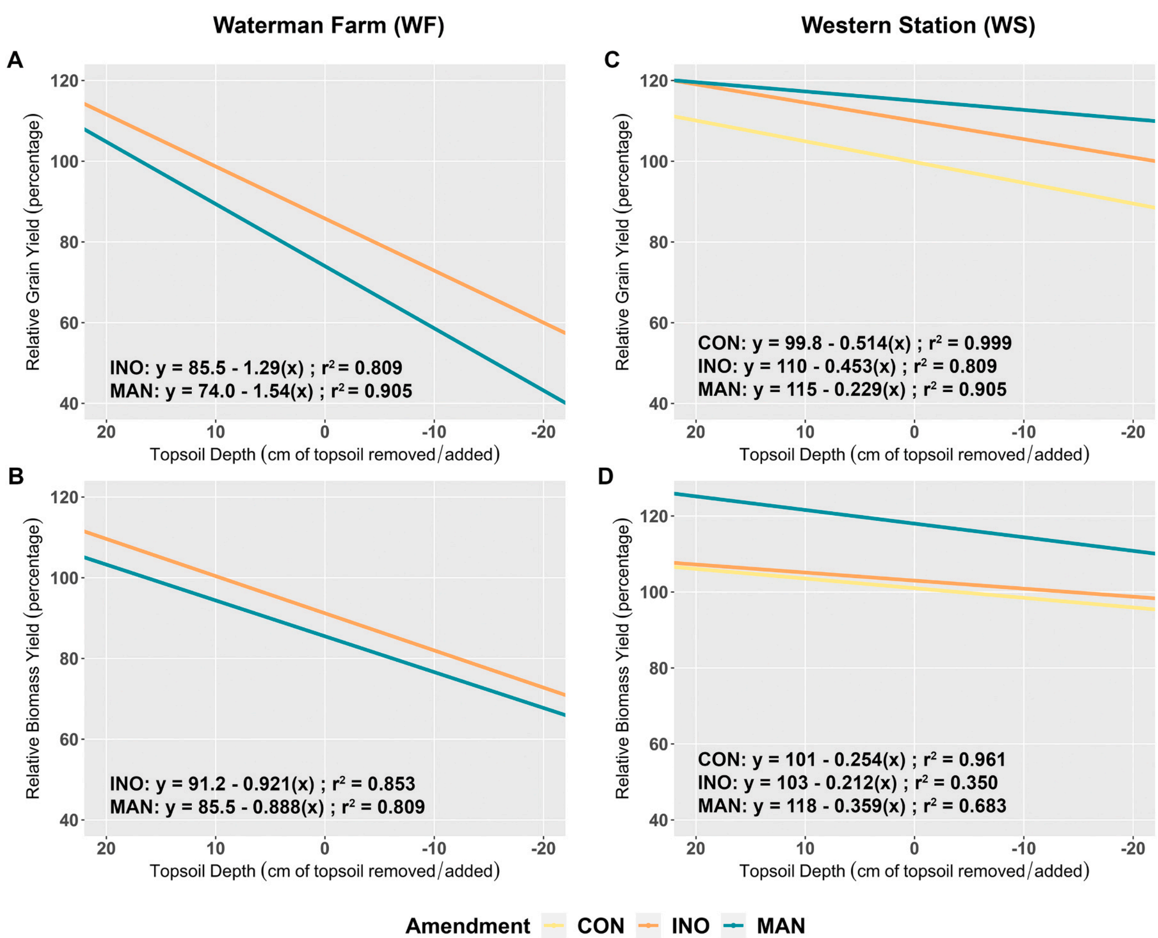

Fig. 6. Erosion-amendment-productivity relationships between topsoil depth and amendment type on average relative maize grain and biomass yields between 2016 and 2020 for the Waterman Farm (WF; A,B) and Western Station (WS; C,D) sites. CON = control (no amendment), INO = inorganic fertilizer, MAN = organic fertilizer.

to TSD and amendment type (Table 1). The rehabilitative effectiveness of amendments to prevent yield decreases varied across field sites. For the WF site, amendment rehabilitative effectiveness followed an order of INO > MAN. The magnitude of the yield responses to amendments can be seen in Table 1. Increases in grain yields were observed for both amendment types at the TSD-2 level for the WF site (INO: 11.3%; MAN: 4.71%). For the TSD-1 level, grain yield decreases of − 26% and − 14.5% were observed for the MAN and INO treatments, respectively. For the TSD-0 level, grain yield declines were − 56.7% for the MAN treatment and − 40.3% for the INO treatment. The INO amended soil netted a 9.60% increase in biomass yields at the TSD-2 level, while the MAN amended soil generated a − 2.03% yield decrease at the same TSD level. For the TSD-1 level, biomass yield declines were observed for both the INO (−8.81%) and MAN (−19.8%) treatments. Similarly, the biomass yield decline gap widened for the TSD-0 level and observed a − 37.5% decrease for the MAN amended soil and a − 27.2% decrease for the INO amended soil.

For the WS site, amendment rehabilitation followed an order of MAN > INO > CON (Table 1). For the TSD-2 level, grain yield increases were observed for all amendment types (CON: 10.1%; INO: 19.4%; MAN:19.2%). For the TSD-1 level, grain yield for the unamended soil decreased − 0.167% while yield gains were observed for both the INO (10.3%) and MAN (14.6%) amended soils. For the TSD-0 level, the unamended soil generated a grain yield decline of − 10.4% while both amended soils generated grain yield increases (INO: 1.25%; MAN:10.0%). Biomass yields followed a similar trend for the TSD-2 level where yield increases were observed for all soil amendments (CON: 6.27%; INO: 25.1%; MAN: 7.38%). For the TSD-1 level, the unamended soil observed a − 1.19% yield decline, while the INO and MAN amended soils observed yield increases of 3.16% and 17.9%, respectively. At the TSD-0 level, biomass yield gains were only seen for the MAN treatment (10.7%). The CON and INO treatments had biomass yield losses totaling − 3.90 and − 1.08%, respectively.

The relationships observed for the WF site demonstrated a net negative effect on grain yield (%) for the MAN treatment compared to the INO treatment. The magnitude of the decline widens greatly with decreasing TSD. The grain yield decreases for the MAN amended soils were − 6.6% for the TSD-2 level, − 11.5% for the TSD-1 level, and − 16.4% for the TSD-0 level. Biomass yield declines were also observed for the amendments and ranged between − 10.3% to − 11.6% for the TSD continuum used in this study (−20 cm topsoil removal to +20 cm topsoil addition). On the other hand, the relationships observed at the WS site showed that the magnitude of grain yield gains widened with decreasing TSD. Grain yield gains from soils receiving the compost manure treatment were 9.1% for the TSD-2 level, 14.8% for the TSD-1 level, and 20.4% for the TSD-0 level. In contrast, grain yield increases from soils receiving the synthetic N fertilizer were 9.3% for the TSD-2 level, 10.5% for the TSD-1 level, and 11.7% for the TSD-0 level. Amendment input assisted in rebounding biomass yields at this site, as well. Biomass yield increases from the MAN amended soils were 1.13% for the TSD-2 level, 19.1% for the TSD-1 level, and 14.6% for the TSD-0 level. Yields from the INO amended soils were 18.8% for the TSD-2 level, 4.35% for the TSD-1 level, and 2.82% for the TSD-0 level. Biomass yield increases varied according to TSD but demonstrated the greatest yield increases when no topsoil removal had occurred. Furthermore, the MAN amended soils had a higher yield gap increase over that of the INO amended soils, indicating a better restorative capacity for that amendment.

3.4. Interrelationships between key soil parameters, biometric agronomic parameters, and yields

Both TSD and soil health can be major determinants of agronomic productivity throughout the growing season and for the harvestable grain and aboveground biomass yields. A Pearson's correlation test revealed several strong significant positive ($r > 0.50$) and negative ($r < -0.50$) relationships between key soil parameters, biometric agronomic parameters, and yields for this study (Fig. 7).

4. Discussion

The findings in this study provide additional insights into the erosion-productivity-amendment relationship, especially for maize cropping systems under long-term management in the U.S. Midwest Corn Belt region. Biometric productivity indices and yields varied drastically between field sites.

4.1. Biometric productivity indices and yields

Topsoil depth significantly influenced productivity indices and yields in this study. Data from both sites support the conclusion that greater TSD translated to greater productivity, grain, and biomass yields, although some were more site dependent than others. Topsoil depth was shown to be strongly correlated with grain yield, germination percentage, and crop stand at both the WF and WS sites (Fig. 7). At the WF site, strong, positive correlations existed between TSD and all productivity and yield parameters signaling that TSD level was more influential on agronomic measurements regardless of soil health status, although TSD level and soil health exhibited a strong, positive relationship with one another (Fig. 7A). At the WS site, the TSD level demonstrated a weak, positive correlation with canopy cover, biomass yield, and harvest index (Fig. 7B). Noteworthy to mention was a lack of correlation between TSD and soil health at the WS site (Fig. 7B). This lack of correlation relationship can be mainly attributed to the variability that was observed in productivity, yield, and soil parameters for some of the TSD levels. Many of the TSD-0-MAN and TSD-1-MAN plots yielded better overall soil health and yields than most of the amended and unamended TSD-1 and TSD-2 soils (Supplemental Materials). Keeping this in mind, soil health status demonstrated more strong, positive correlations with grain and biomass yields and canopy cover at the WS site. As soil rehabilitation occurs, soil health may play a larger role in agronomic productivity and yields more than TSD because the resulting improvements in soil properties in the exposed subsoil now match those properties of the undisturbed topsoil or topsoil added with a duplicate layer. Canopy cover and grain yield proved to be two of the most important indicators of how TSD and soil health can impact plant growth and shape what yield potentials may resemble.

Observed productivity and yield for the TSD-0 level, especially at the WF site, are likely due to suboptimal soil conditions (higher bulk density, lower water stable aggregates, lower water infiltrability and movement, etc.) (Table S1). These suboptimal soil properties resulted in subpar soil health levels that contributed to growing conditions that were not conducive for adequate crop establishment and subsequent growth and development through the growing season (Moonilall, 2022). Across most growing seasons for both sites, precipitation totals during April/May were observed to be greater than the 10-year average observed for the region leading to prolonged standing water in the field (Fig. 1B; Fig. S4). This was directly caused by a breakdown in soil structure and pore architecture leading to poor infiltrability and drainage (Table S1). These soils had an insignificant capacity to absorb water through the soil-atmosphere interface and transmit water downward into the soil profile (Moonilall, 2022). Additionally, because of this, erosional activity was further intensified mainly because of enhanced surface crusting at the soil surface contributing to overall lower rates of water absorption for these soils in relation to the rates of precipitation the site was receiving at the time. The areas where greater TSD was present (e.g.,TSD-1 and TSD-2) observed better crop growth and yields mainly due to greater soil health, especially for crucial physical soil health indicators (Tables S1 and S2).

Agronomic data from this study demonstrated that greater TSD netted significantly greater grain and biomass yields. Grain yield for both sites ranked in the following order: TSD-2 > TSD-1 > TSD-0.

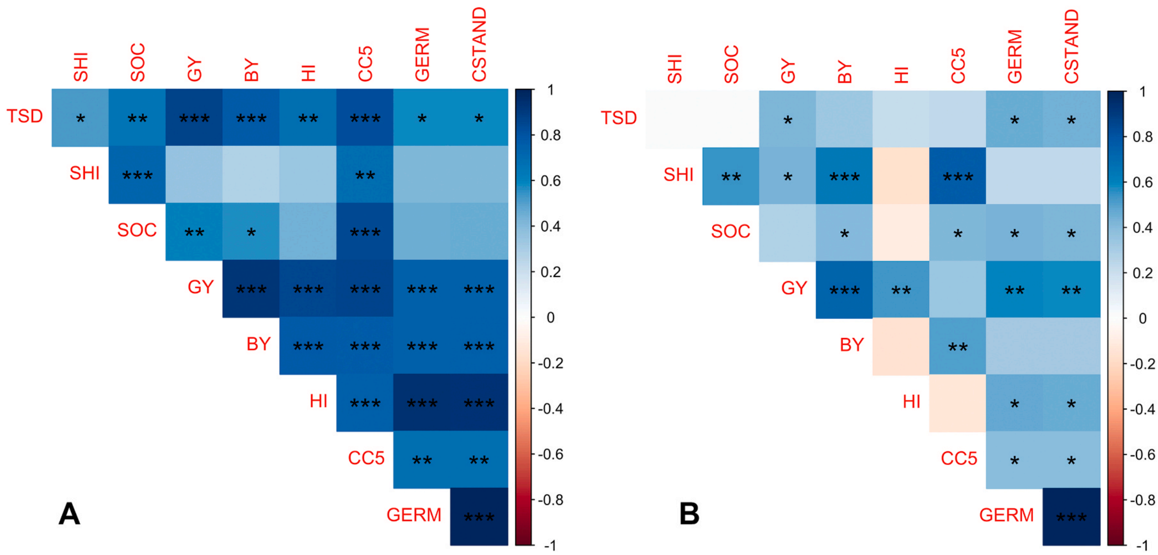

Fig. 7. Pearson's correlation test for varying soil and agronomic parameters for the Waterman Farm (WF) (A) and Western Station (WS) (B) sites. *, **, *** indicates level of significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. TSD = topsoil depth, SHI = soil health index, SOC = soil organic carbon stock, GY = grain yield average, BY = biomass yield average, HI = harvest index average, CC5 = canopy cover percentage 5 weeks after germination average, GERM = germination percentage average, CSTAND = crop stand average. All of the aforementioned averages (except for CC5) are over a 5 year period between 2016 and 2020. The averages for CC5 are across a 3/4 year period (2017–2020).

Biomass yield for both sites ranked in the following order: TSD-2 ≥ TSD-1 > TSD-0. Pooled 5-year yields demonstrated that the TSD-0 treatment continued to generate significantly lower yield output than both the TSD-1 and TSD-2 treatments. The WF site observed wider yield gaps between the TSD-0 level and the TSD-1 and TSD-2 levels. However, at the WS site, although yields for the TSD-0 level were the lowest, the yield gaps between this TSD level and the TSD-1 and TSD-2 levels were narrower, indicating that TSD-0 yields were rebounding in a positive direction.

4.2. Rebounding impact of amendments on productivity and yields after erosion has taken place

Negative impacts produced through the erosional process can be reversed when BMPs coupled with copious soil amendment inputs are incorporated into a soil management plan. Sustainable soil management practices that adhere to minimizing soil disturbance, providing continual soil cover, and diversifying crops and cropping patterns provide benefits that improve soil physical, chemical, and biological soil properties that translate to improvements in agronomic yields (Ren et al., 2023). Stand-alone implementation of reduced/ no-tillage, crop residue retention, organic amendment inputs, cover crops, and crop rotations have individually been shown to improve soil properties leading to greater functionality related to the cropping system's targeted goals (Lehman et al., 2015; Tully and McAskill, 2020). Implementation of several of these management strategies creates a "stacking" effect and generally leads toward adaptive, additive, and synergistic benefits to soil health (Lehman et al., 2015; Tully and McAskill, 2020; Wade et al., 2022). Stacking of soil health management practices is demonstrated at both experimental sites where no-tillage, crop residue retention, and organic inputs are part of the management strategy to rehabilitate eroded soils. For each site, the INO plots have no-tillage + residue retention while MAN plots have no-tillage + residue retention + organic input. The CON plots at the WS site are managed with no-tillage + residue retention without any amendment input. Several studies have indicated that stacking sustainable management practices in maize cropping systems not only induced better soil properties overall but produced greater yields compared with soils that did not follow sustainable management practices (use of tillage, no soil cover, strict use of chemical inputs, etc.) (Nunes et al., 2018; Lehman et al., 2015; Tully and McAskill, 2020).

Grain and biomass yields across both sites were influenced differently according to amendment type. At the WF site, the INO treatment (urea fertilizer) exerted a greater influence on overall yields than the MAN treatment (compost manure). At the WS site, the influence of amendments on overall yields followed the order of MAN > INO > CON (unamended). Several studies have reported on the effectiveness of different soil amendments to improve agronomic yields. Larney et al. (2009) ranked soil amendments in the following order based on their overall effectiveness in fixing wheat yield losses: manure > topsoil > chemical fertilizer. Zhou et al. (2012) ranked manure+fertilizer combination > fertilizer for rehabilitating root growth and dynamics in maize crops. Sui et al. (2017) and Zhou et al. (2015) similarly ranked amendments in the following order of their effectiveness at rebounding maize and soybean yields: manure+fertilizer combination > fertilizer. Larney and Janzen (1996) suggested that manure (swine, poultry) was optimal for restoring yields on eroded soils followed by crop residues (alfalfa (*Medicago sativa*) hay, pea (*Pisum sativum*) hay) and fertilizers (N, P). The frequency of amendment application to cropping systems and the kind of amendment(s) used dictated how fast (or slow) crop yields can rebound in these systems (Larney and Angers, 2012). Some studies utilized a one-time soil amendment application that occurred early in the experiment (Izaurralde et al., 1998, 2006; Larney et al., 2000, 2011, 2016) while others utilized repeated, annual soil amendment application (Jagadamma et al., 2009; Zhou et al., 2012, 2015; Li et al., 2020). It appears that those studies that utilized a one-time amendment application observed crop yields improve drastically in the short-term soon after the onset of the study. The legacy effect of those amendments also continued to persist many years after the start of the study (Larney and Olson, 2018). Aside from soil amendment application, other contributing factors could impact maize productivity and yields such as soil nutrient status and weather, and could demonstrate why contrasting results were seen for the amended soils at the experimental sites in this study.

Repeated, annual amendment application rebounds crop yields on a more stable basis. Yields for soils with severe TSD reduction rebound faster and narrow the yield gap (compared with uneroded soil) better with repeated amendment application rather than a one-time application (Jagadamma et al., 2009; Zhou et al., 2012, 2015; Zhang et al., 2021). Several mechanisms influence the mitigative capacity of soil amendments to rehabilitate crop yields: greater plant available nutrients (such as N) present from amendment addition, increase in nutrient cycling and retention of plant available nutrients through soil organic matter (SOM) cycling and addition, increase in net primary productivity (NPP) both above- and belowground caused by nutrient availability effects and increased crop yields, and increase in pedogenesis stemming from improved soil health due to amendment application and SOM cycling (Larney et al., 2016; Celestina et al., 2019). The coupling of these factors may be one of the primary reasons why some amendments perform better at rebounding yields in eroded soils than others. Nutrient dynamics play a big role in this regardless of amendment type (Hijbeek et al., 2017; Schjønning et al., 2018; Celestina et al., 2019), but organic amendments usually add another dynamic that facilitates an earlier kick-start towards rebuilding soil health (Larney and Angers, 2012; Kneller et al., 2018; Wang and Li, 2019). Organic amendments have been shown to enhance biological activity belowground and stimulate the faunal and microbial communities (Larney and Angers, 2012; Larney et al., 2016). This enhancement in biological activity creates a positive feedback loop that then produces greater crop yields, which add more organic matter back to the soil system in the form of crop residues and belowground inputs (Berhe et al., 2007). Simultaneously, organic-based additions, on their own, contain greater binding agents and effectively promote the production of more belowground biomass through plant growth (Piccolo and Mbagwu, 1990). The enhanced soil biological communities also contribute towards enhancing greater nutrient cycling leading to greater accrual in plant-available nutrient pools and SOC pools (Shrestha et al., 2009; Malik et al., 2013; Sekaran et al., 2020). Additionally, it promotes greater soil aggregate formation that serves to further stabilize and protect SOC, thus leading and contributing to pedogenesis within the eroded soil profile (Maiti and Ahirwal, 2018; Spasić et al., 2021).

SOC pools in agroecosystems have a direct influence on agronomic yields. SOC and agronomic data from the two sites support that greater SOC pools translated to greater grain and biomass yields (Fig. 7). The C input into cropping systems is crucial for maintaining and bolstering overall soil health and SOC pools, which in turn impacts agronomic yields, mainly through nutrient cycling and nutrient (mainly N) availability (Edmeades, 2003). Both experimental sites in this study used stacked soil management practices where maize residue was retained on the soil surface as a mulch at the end of the season and belowground biomass (roots) were left intact since no-tillage management is practiced. These factors contribute to the overall system NPP and the subsequent C allocation that is returned each growing season (aside from the soil amendment input) (Edmeades, 2003). A decline in NPP caused by erosional processes can create a feedback loop that jeopardizes the C input that stems directly from crop growth. Declines in NPP and the resulting potential losses in C inputs to the soil, stemming from grain and biomass yields from the reference systems (mentioned earlier), were calculated through maize C allocation coefficients, similar to calculated wheat estimates performed in Larney et al. (2009), using the method outlined in Bolinder et al. (2007). C inputs were calculated for various components of the maize plant (grain, biomass, roots, root exudates) based on yield results obtained from this study as well as general information regarding maize cropping systems in the U.S. Corn Belt region. Cumulative yield losses (kg ha^{-1} cm^{-1}) over the five-year study period were 1213 for the WF site and 507 for the WS site (Table 2). The estimated C input losses from these systems assumed that grain, biomass, roots, and root exudates had biomass C concentrations of 45%. This resulted in cumulative C losses (kg ha^{-1} cm^{-1}) spanning the five-year study period to total 546 for the WF site and 228 for the WS site. Since grain is exported out of the system, the C allocation from this component was subtracted from the cumulative C value, thus resulting in incurred cumulative C input losses (kg ha^{-1} cm^{-1}) of 257 and 89 for the WF and WS sites, respectively. This translated to an estimated C input loss (Mg ha^{-1}) of 5.14 for the WF site and 1.78 for the WS site. Aside from the amendment C input allocation, this may also assist in explaining the severity of the productivity and yields seen in the TSD-0 level at the WF site, since these estimated losses are for what could be incurred when no form of rehabilitation (amendment application) is implemented. The overall C inputs entering the TSD-0 system are always going to be less than the TSD-1 and TSD-2 systems. SOM cycling and resulting nutrient cycling remain low in these systems and not only limit the plant available nutrient capacity for these soils, but also the transformative abilities to improve soil properties that are conducive for optimal crop growth (Kirkby et al., 2011).

4.3. Critical threshold values for maize grain and biomass yields

Critical threshold values for maize biomass and grain yield losses varied between sites. Relative biomass yield losses were 0.921% cm^{-1} for the WF site and 0.254% cm^{-1} for the WS site. Relative grain yield losses were 1.29% cm^{-1} for the WF site and 0.514% cm^{-1} for the WS site. A review by den Biggelaar et al. (2004) estimated that mean maize yield losses for Alfisols in North America were 1.30–2.60% cm^{-1}. This range was derived from several TSD and topsoil removal/addition studies across several U.S. states and the Ontario, Canada region. A

Table 2
Estimated C input losses from the Waterman Farm (WF) and Western Station (WS) maize systems based on five-year yield loss estimates.

Site	Maize Component	Mean Yield (2016–2020)[a]	Annual yield loss		Cumulative yield loss (2016–2020)	Cumulative C loss (2016–2020)[b]	Cumulative C input loss to soil (2016–2020)[c]
		Mg ha^{-1}	% cm^{-1}	kg ha^{-1} cm^{-1}	kg ha^{-1} cm^{-1}	kg ha^{-1} cm^{-1}	kg ha^{-1} cm^{-1}
Waterman Farm (WF)	Grain	9.95	1.29	128	642	289	0
	Biomass	8.97	0.921	83	413	186	186
	Roots			19[d]	96	43	43
	Root exudates			12[e]	62	28	28
	Total			242	1213	546	257
Western Station (WS)	Grain	12.0	0.514	62	309	139	0
	Biomass	10.4	0.254	26	132	59	59
	Roots			8[d]	40	18	18
	Root exudates			5[e]	26	12	12
	Total			101	507	228	89

[a] Mean yields from reference treatment.
[b] Assumes the C concentration for all maize components is 45%.
[c] Assumes that all maize components, except for grain, are returned back to the soil.
[d] Maize C allocation coefficients of 0.870 for grain and biomass and 0.079 for roots. Calculated using the method from Bolinder et. al. (2007).
[e] Maize C allocation coefficients of 0.870 for grain and biomass and 0.051 for root exudates. Calculated using the method from Bolinder et al. (2007).

review by Bakker et al. (2004) estimated mean yield losses from various studies across the world ranged between 0.66% and 2.66% cm^{-1}. Relative grain and biomass yield losses for both sites in this study are below the critical threshold ranges provided by this review.

Mean biomass yield declines (Mg ha^{-1} cm^{-1} yr^{-1}) were 0.083 at the WF site and 0.026 at the WS site. Mean grain yield declines (Mg ha^{-1} cm^{-1} yr^{-1}) were 0.128 for the WF site and 0.061 for the WS site. den Biggelaar et al. (2004) estimated that mean erosion-induced maize yield losses for Alfisols in North America ranged between 0.092 and 0.153 Mg ha^{-1} cm^{-1} yr^{-1}. The threshold mean grain yield loss for the WF site is within this estimated range. Contrarily, the threshold grain value for the WS site is far below this range.

4.4. Diminishing deleterious erosional effects back to pre-eroded conditions

Data from this five-year study indicate that the deleterious effects of erosion were found to be reversed with the addition of INO and MAN amendments at the WS site (Table 1). Average grain and biomass yields maintained greater amounts than the TSD-0-C treatment when 20 cm of topsoil was removed. Grain yield for the MAN treatment was shown to be 4.6% greater relative to the reference treatment, while the yield for the INO treatment was nearly 2.1% greater. The biomass yield increase relative to the reference treatment was 7.9% greater for the MAN treatment and 2.3% greater for the INO treatment. The deleterious effects of erosion at the WF site were not reversed through amendment application (Table 1). Grain yield, on average, was shown to be 55% lower than the reference treatment, while biomass yield was nearly 37% lower.

The impact of soil amendments on agronomic yields become more pronounced and realistic as greater time elapses, especially for topsoil removal/ addition studies (Larney and Olson, 2018; Karlen and Obrycki, 2019). Across both the WF and WS sites, the degree of change for grain and biomass yields for the 14 years between 2006 and 2020 resulted in net positive increases across all TSD levels and amendment types, indicating growing productivity with increasing time duration (Table 3). Furthermore, as greater time elapsed from the onset of the study, yield reductions between TSD increments become smaller when compared to a time point earlier on in the study, due to the restoration in productivity and yields resulting from a greater soil nutrient supply, improvements in soil health, and a growing SOC pools (Bakker et al., 2004; Larney et al., 2009; Kirkby et al., 2011).

Several studies reported that yields can be rebounded back to pre-eroded conditions with BMPs and sustainable agricultural management practices in place (Larney et al., 2009; Burger et al., 2023) while others may require longer durations to fully recover (Larney and Olson, 2018) or not recover at all (Zhang et al., 2021). Technological advancements in crop cultivars (through crop breeding) and judicious use of sustainable soil management can play a key role in this, especially when stacked along with soil amendment application. A meta-analysis from Zhang et al. (2021) reported that crop yield restoration was possible if the depth at which the topsoil loss occurred was < 5 cm, but limited when the depth is > 10 cm. They concluded that when topsoil loss exceeds 25 cm, crop yields cannot be restored to pre-eroded conditions, even when soil amendments and BMPs are implemented (Zhang et al., 2021). This may be true for some soils in some regions of the world, but this notion further warrants the need for longer-term studies. Enhancing and shifting the soil biological community to enhance soil microbial community structures may be able to increase the speed at which pedogenesis occurs, thus allowing for greater success at rebounding crop yields where severe TSD depletion has occurred (Li et al., 2015). The kind of amendment used, application rate, and frequency of application early in the restoration process will ultimately dictate how successful pedogenesis is at restoring crucial soil properties and how it will influence rebounding crop yields. Using organic soil amendments to restore eroded soils will be the fastest, most efficient, and cost-effective option to reinvigorate soils leading to enhanced crop productivity and yields (Larney and Angers, 2012). As greater time elapses with the use of these kinds of amendments, soils can experience self-renewal not only in soil properties but in NPP, leading to greater crop productivity. Just as the influence of soil erosion on agronomic productivity varies across time and space, the rehabilitative capacity of soil amendments to restore agronomic productivity also varies across time and space.

Table 3
Mean grain and biomass yields (Mg ha^{-1}) and resulting net changes (%) between 2006 and 2020 at the Waterman Farm (WF) and Western Station (WS) sites.

	Grain Yield (Mg ha^{-1})			Biomass Yield (Mg ha^{-1})		
Year	2006[a]	2020[b]	Change (%)	2006	2020	Change (%)
	Waterman Farm (WF)					
TSD[c]						
0	3.1	5.22	+ 68	4.2	4.21	+ 0.2
1	5.6	8.58	+ 53	4.8	6.31	+ 31
2	7.8	10.5	+ 35	5.8	7.98	+ 38
Amendment[d]						
INO	5.8	8.55	+ 47	5.1	6.30	+ 24
MAN	5.4	7.65	+ 42	5.0	6.03	+ 21
	Western Station (WS)					
TSD						
0	8.2	11.5	+ 40	7.0	12.1	+ 73
1	9.0	14.5	+ 61	7.7	13.2	+ 71
2	9.3	14.0	+ 51	8.6	13.4	+ 56
Amendment						
CON	8.8	12.9	+ 47	7.3	12.7	+ 74
INO	8.8	14.0	+ 59	7.2	12.3	+ 71
MAN	9.0	13.2	+ 47	8.1	13.7	+ 69

[a] Data for 2006 yields obtained from Jagadamma et al. (2009).
[b] Data from Moonilall (2022).
[c] TSD = topsoil depth, TSD-0 = 20 cm of topsoil removal, TSD-1 = no topsoil removal, TSD-2 = 20 cm of topsoil added.
[d] CON = control (no amendment), INO = inorganic fertilizer, MAN = organic fertilizer.

5. Conclusions

We assessed maize productivity and yields using specific indicators on two truncated soils in Central Ohio and evaluated restorative capacity using inorganic and organic soil amendments. Our study findings support the following conclusions:

- Maize biometric productivity parameters and yields were greater with increasing TSD. Maize germination and growth under the TSD-0 level were lower and slower compared to that of the TSD-1 and TSD-2 levels, as seen in the canopy cover development over the first five weeks after germination. Lackluster growth translated to lesser grain and biomass yields with lower TSD levels.
- The addition of compost manure and N fertilizer, respectively, improved many biometric productivity parameters. However, annual yields varied between sites. For the WF, the addition of the synthetic N fertilizer resulted in greater yields, while the input of compost manure at the WS resulted in greater overall yields.
- The rehabilitative capacity of the soil amendments, in terms of crop productivity, varied between sites, with either the N fertilizer or compost manure having better restorative ability. Maize grain and biomass yields for soils with severe TSD reduction were able to rebound faster and narrow the yield gaps (compared with uneroded soil) better with repeated compost manure amendment application.
- Amendment application with N fertilizer or compost manure coupled with BMPs (no-tillage, crop residue retention, organic matter input, etc.) were able to rebound yields to pre-eroded conditions at the WS site, with the greatest impact observed in the TSD-0 soils amended with compost manure. Improvements in soil health stemming from

annual amendment application coupled with BMPs were able to alleviate the deleterious effects caused by erosion. Results from this study demonstrate that maize grain and biomass yields cultivated from Crosby soils (Luvisols) in the U.S. Corn Belt can be restored to pre-eroded condition with the application of organic (animal manure compost) or inorganic (urea fertilizer) amendments.

CRediT authorship contribution statement

Nall I. Moonilall: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Kyle Sklenka:** Software, Resources, Writing – review & editing, Visualization. **Mallika A. Nocco:** Resources, Writing – review & editing, Visualization, Supervision. **Rattan Lal:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision of the NC-1178, Project administration, Funding acquisition, and Major Dissertation Advisor of Nall I. Moonilall.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Acknowledgments

The experiments reported herein were part of the North Central Regional Research Committee (Project NC-1178) which involved multi-state members from several U.S. Land Grant Universities and the United States Department of Agriculture (USDA). N.I.M. is appreciative of the funding support provided by the Environmental Science Graduate Program (ESGP), School of Environmental and Natural Resources (SENR), and CFAES Rattan Lal Center for Carbon Management and Sequestration (Lal-CMASC) at The Ohio State University. Authors extend thanks to the farm managers at both research sites used in the study - Mr. Glenn Mills from the Waterman Agricultural and Natural Resources Laboratory and Mr. Joe Davlin from the OARDC Western Agricultural Research Station – for their assistance in maintaining the research plots and for providing soil amendments annually. Lastly, thanks are extended to Mr. Basant Rimal for his assistance with the in-field harvesting of aboveground biomass and processing of grain.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2023.109178.

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