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Evaluating corn, tall fescue and canola growth on sediments dredged from the Lorain Harbor

Maureen E. Roddy[1] | **Emily Kalhert**[1] | **Corry T. Platt**[2] | **Ashley N. Julian**[3] | **Megan A. Rúa**[1,3]

[1]Department of Biological Sciences, Wright State University, Dayton, Ohio, USA

[2]Geosyntec Consultants, Raleigh, North Carolina, USA

[3]Environmental Sciences PhD Program, Wright State University, Dayton, Ohio, USA

Correspondence
Megan A. Rúa, Department of Biological Sciences, Wright State University, 3640 Colonel Glenn Hwy, Dayton, OH 45435, USA.
Email: megan.rua@wright.edu

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Abstract

Soil degradation is a worldwide problem, causing the declining performance of many plant species. Recently, the application of sediments dredged from aquatic waterways has received attention for their potential as an organic amendment to revive degraded agricultural soils. In Ohio, dredged sediment research has largely focused on the success of corn (*Zea mays*) or soybean (*Glycine max*) following the application of dredged sediments from the Toledo Harbor, neglecting the potential for dredged sediments from the other eight harbors and waterways to change plant performance as well as failing to quantify benefits for other commonly grown crops in the region. In a greenhouse experiment, we applied dredged sediments from the Lorain Harbor to degraded agricultural soils across a variety of application ratios and quantified changes in germination, height over the growing season, final biomass, and yield for canola (*Brassica napus*), tall fescue KY 31 (*Festuca arundinacea*), and corn to better understand the potential for dredged sediments from this location to increase performance for a variety of regionally important plant species. Overall, plants grown on agricultural soils supplemented with dredged sediments from the Lorain Harbor consistently grew taller, faster, and were larger than the 100% dredged sediment treatments. Furthermore, both corn and tall fescue grown on agricultural soil supplemented with dredged sediments had greater yield compared to their counterparts grown on unamended agricultural soil. In whole, outcomes from this research contribute to a growing body of research that support the use of dredged sediments as a soil amendment for agricultural soils.

1 | INTRODUCTION

Agriculture plays a pivotal role in the global economy, representing approximately 12% of the global gross domestic product, which translates to $10 trillion and 40% of all jobs (World Economic Forum, 2020). To maintain this level of agriculture, farming practitioners employ a number of intensive agricultural production techniques including large mono-cropping systems that change soil structure, vegetation, and community structures of microorganisms, insects, and animals (Villamil et al., 2006). The continual use of such systems can have long-term detrimental effects on soils including declines in physiochemical and biological properties related to several metrics of overall plant performance including biomass and yield (Gomiero, 2016; Thaler et al., 2021).

To combat soil degradation, several management strategies have been developed. Among the most common is the application of an organic soil amendment. Organic amendments can take the form of animal manure, municipal biosolids, and manufacturing wastes. Recently, sediments removed from aquatic waterways have received attention for their possible use as an organic amendment (Brigham et al., 2021; Darmody & Marlin, 2002; Julian, 2023; Julian et al., 2023). These sediments have the potential to increase production in low-/nonproducing areas due to their ability to improve soil characteristics as a result of their high soil fertility, organic matter, and water holding capacity (Darmody & Marlin, 2002; Koropchak et al., 2016; Sigua, 2005). Additionally, when dredged sediments turn terrestrial, they contain microorganisms important for nutrient cycling (Rúa et al., 2023). These attributes can improve overall soil health and lead to increases in overall yield and crop production (Canet et al., 2003; Daniels et al., 2007; Darmody & Diaz, 2017; Julian et al., 2023).

Previous work in other freshwater systems examining the potential for dredged sediments to be used as agricultural amendments has largely found positive results in their success. Weathered sediments from the Illinois River supported plant growth in both the greenhouse and field (Darmody & Diaz, 2017; Darmody & Marlin, 2002; Julian et al., 2023). However, these experiments did not compare plant growth in dredged sediments to growth in traditional agricultural soils, so the magnitude of the benefit could not be accurately assessed. Sediments from central Illinois lakes also supported plant growth when used as a soil amendment for eroded soils (Lembke et al., 1983), but this effect was not evaluated with respect to control soils. In an experiment that did compare growth between soils amended with dredged sediments and without dredged sediments from Lake Panasoffkee, Florida increased forage yield and crude protein content of bahiagrass (Sigua, 2005).

The mixed results for plant performance when dredged sediments were used as a soil amendment may reflect a lack of guidance on proper application rates. Other soil amendments, such as manure or biosolids, are applied using the nutrient recovery ratio, which considers the amount of nutrients necessary for plant growth for the specific crop of interest and calculates the amount of amendment necessary to bridge the gap between current nutrient concentrations in the agricultural soil and nutrient concentrations expected to be provided by the proposed amendment (Guo, 2020). However, when this ratio is applied for dredged sediments, application ratios based on the nutrient recovery ratio failed to alter plant growth and yield for both corn and soybean compared to 100% pure agricultural soils (Julian, 2023). Consequently, additional research evaluating appropriate application ratios of dredged sediments to agricultural soils is needed.

Core Ideas

- Dredged sediments were evaluated for their potential to increase plant performance when used as a soil amendment.
- All three species grew taller and faster in soils supplemented with dredged sediments compared to 100% dredged sediments.
- Both corn and tall fescue had greater yield on agricultural soils with dredged sediments than 100% agricultural soils.

Although previous studies on the effect of dredged sediments from Ohio on corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) performance exist (Brigham et al., 2021; Julian et al., 2023), farmers need to understand its potential use with additional regionally important forage and turfgrass species, including canola (*Brassica napus* L.) and tall fescue (*Festuca arundinacea* Schreb. var. KY31). Furthermore, understanding the effect of Lorain Harbor sediments, and their appropriate application ratio, on plant performance is particularly important to understand due to the extremely high organic content of these sediments compared to the well-researched sediments from the Toledo Harbor (Brigham et al., 2021; Julian, 2023; Julian et al., 2023; Rúa et al., 2023). Therefore, we sought to quantify plant performance for corn, canola, and tall fescue grown across a variety of agricultural soil to dredged sediments ratios to identify the appropriate application ratio and better understand the role of dredged sediments from the Lorain Harbor for altering plant performance.

2 | METHODS

2.1 | Experiment description and preparation

To investigate the use of dredged sediments from the Lorain Harbor as a beneficial soil amendment, we factorially manipulated the ratio of agricultural soil to dredged sediments by volume consistent with the following treatments: 100:0, 10:90, 30:70, 50:50, and 0:100 (corn), and 100:0, 30:70, 50:50, 70:30, and 0:100 (canola and tall fescue). Each treatment was replicated five times for a total of 75 experimental pots (5 soil mixes × 3 focal species × 5 replicates). Sediments were hydraulically dredged from the federal navigation channel of the Black River, rapidly dewatered using GeoPool technology (Ellicott Dredge Technologies, LLC), and exposed to one freeze-thaw cycle prior to use. Exposure to a freeze-thaw cycle is important for dredged sediments to develop an appropriate soil structure (i.e., break up aggregates and increase organic carbon [C] content) and can be important for stimulating microbial activity (Vermeulen et al., 2003). Agricultural farm soil was sourced from an actively farmed field in Lorain County, Ohio. For both dredged sediments and agricultural farm soil, materials were extracted from multiple locations in the field/GeoPool and placed in multiple five-gallon buckets. Subsamples were composited from the buckets to create a representative sample of the 100% agricultural soil and 100% dredged sediments. Subsamples were sent to A&L Great Lakes Laboratories, where a standard suite of agronomic soil parameters were measured prior to creating the ratio treatments (Table S2). All materials were collected during the last week of March 2021 before being transported to Wright State University (WSU), Dayton, OH, on April 5, 2021. Materials were stored in the greenhouse for immediate use. Soil ratios were homogenized by hand and made in large batches prior to planting.

Dredged sediments had an organic matter content at 1382°F of 7.4% and were classified as an elastic silt (19.8% fine sands, 51.5% silt, and 28.7% clay). The agricultural soil had an organic matter content at 1382°F of 5.8% and was classified as a clay (17.4% fine sand, 44.4% silt, and 38.1% clay). Of the agronomic parameters measured, phosphorus (P) (Bray-2 equivalent), exchangeable calcium (ppm), soluble salt concentration (1:2), zinc (ppm), and manganese (ppm) were all double in the dredged sediments compared to the agricultural soil (Table S2). Conversely, phosphorus (Mehlich 3) was double in amount in the agricultural soil compared to the dredged sediments (Table S2). All other values were similar, although statistical significance could not be determined due to lack of replication.

Experimental plants were grown in one-gallon pots (corn and canola) or D20 Stuewe & Sons pots (tall fescue). Three seeds were planted for canola (Gardens Alive!, Inc.) and tall fescue (The Scotts Company, LLC), and two seeds for corn (Pioneer and Corteva Agriscience). Germination was recorded and plants were thinned to a single plant per pot approximately 3 weeks after germination for canola and corn and 4 weeks after germination for tall fescue. All pots had at least one germinant per pot.

2.2 | Greenhouse conditions

All plants were grown in the WSU greenhouse (average 79.2°F with 41.03% humidity). The greenhouse was supplemented with 150–250 μmol/m^2/s light on an 8-h on, 16-h off cycle consistent with the natural day/night cycle. Plants were watered with standard tap water every other day until senescence (corn) or harvest (tall fescue and canola).

2.3 | Soil responses

Approximately 1 lb (500 g) of soil from each pot was collected immediately prior to planting (April 26, 2021) and again at the final harvest (tall fescue and canola: June 14, 2021, and corn: September 17, 2021). We measured six physicochemical properties on these samples: soil texture (% sand, % silt, and % clay), soil compaction, gravimetric water content, bulk density (BD), pH, and conductivity (μS/cm).

Soil texture was assessed with a LaMotte soil texture kit (LaMotte) following the manufacturer's instructions. Soil compaction was measured at the final harvest with a Dickey–John penetrometer (Churchill Industries). Briefly, we added 100 mL of water to each pot to ensure the soil was moist prior to using the 0.5-in. tip recommended for firm soil types to record the pressure range (green < 200 psi, yellow = 200–300 psi, and red > 300 psi) at a depth of 3 in. in each pot.

Gravimetric water content and BD were quantified using the protocol outlined in Onufrak et al. (2020). Briefly, 0.04 lbs of each sample ("subsample wet mass") was dried for 48 h at 221°F, then weighed to obtain the dry mass of each subsample ("subsample dry mass"; Equation 1).

$$\% = \left(\frac{\text{Subsample wet mass} - \text{subsample dry mass}}{\text{Subsample dry mass}}\right) \times 100 \tag{1}$$

BD was quantified as a function of the volume of soil at harvest ("moist volume"; determined by weighing the contents of the pot at harvest), and then a small subsample was weighed wet ("subsample wet mass"), dried for 48 h at 221°F, and weighed again to determine the moisture of the soil ("moist mass"; Equation 2).

$$\text{g/mL} = \frac{\text{Moist mass}}{\text{Moist volume}} \times \frac{\text{Subsample dry mass}}{\text{Subsample wet mass}} \tag{2}$$

Soil pH was assessed following the 1:2 soil-to-water ratio protocol outlined in Woods et al. (2019). Briefly, 0.03 lbs of each soil sample was added to 30 mL of Milli-Q water, in duplicate, and shaken by hand for 30 s to form a soil slurry. The slurry then sat for 30 min and was read on a Fisherbrand accumet AB15 Basic and BioBasic pH/mV/°C Meter (ThermoFisher) by inserting the probe into the liquid upper layer. Electrical conductivity was measured on the same samples prepared for soil pH with a Traceable Conductivity/Total Dissolved Solids Meter (Cole-Parmer). For both pH and conductivity, the average of each duplicate pair was taken to generate one value for each sample. One tall fescue soil sample in the 100% agricultural soil treatment was lost during processing, so that sample was excluded from soil property analyses for pH and conductivity because there was not enough material for those analyses.

2.4 | Plant responses

Two focal plant species (canola and tall fescue) were monitored for 45 days before being destructively harvested (April–June 2021). Corn was allowed to complete its lifecycle and grew for 21 weeks (~145 days; April–November 2021). We recorded germination and measured height over time (all plants), leaf count (all plants), tillering (tall fescue), ear production (corn), and above- and below-ground biomass (all plants). Leaf count and plant height measurements were taken weekly throughout the growing season, starting from plant emergence on May 3, 2021, and continuing until harvest following USDA-recommended protocols. For corn, height (in.) was measured from the bottom of the plant, even with the soil, to the top of the arch of the highest fully formed leaf (Nafziger, 2017). Similarly, the leaf count was measured by counting only the fully formed leaves with an arch. Height and leaf count for canola were measured in a similar fashion. For tall fescue, height was measured from the bottom of the plant, even with the ground, until the tip of the tallest blade, and leaf count was measured based on the production of new nodes that give rise to fully formed leaf blades (Fribourg et al., 2009). Daughter tillers were also counted as indicators of reproduction.

Above- and below-ground biomass were measured at the final harvest. Once the plants were harvested (initial or final), the roots were disconnected from the stalk and cleaned to remove excess soil. All roots and plant materials were dried for 48 h at 221˚F, and biomass (lbs) was recorded. Total biomass is the sum of above- and below-ground biomass.

2.5 | Analysis

All analyses were conducted in R version 4.3.0 (R Core Team, 2023). Germination rate was estimated using the *drmte()* function with the nonparametric maximum likelihood estimator for censored time-to-event data ("NPMLE()" function) in the "drcte" R package (Onofri et al., 2022). A one-way analysis of variance (ANOVA) was used to determine if total biomass and final height differed by agricultural soil:dredged sediment ratio with a random effect for block using the *lme* and *anova* functions from the stats package (R Core Team, 2023). A two-way ANOVA was used to determine if plant height varied by the interaction of time and agricultural soil:dredged sediment ratio with a random effect for block using the *lme* and *anova* functions from the stats package (R Core Team, 2023). A generalized linear model with the Poisson distribution was used to determine if the number of tillers (tall fescue) or ears (corn) produced differed by agricultural soil:dredged sediment ratio and time of assessment using the *glm* function from the *stats* package (R Core Team, 2023).

In independent models, a one-way ANOVA was used to determine if soil texture (% sand, % silt, and % clay), gravimetric water content, BD, pH, or conductivity varied based on the ratio of agricultural soil:dredged sediment with a random effect for block using the *lme* and *anova* functions from the stats package (R Core Team, 2023). In separate models for each species, a two-way ANOVA was used to determine if plant biomass varied by the interaction of any of the soil properties (soil texture [% sand, % silt, and % clay], gravimetric water content, BD, pH, or conductivity) and agricultural soil:dredged sediment ratio with a random effect for block using the *lme* and *anova* functions from the stats package (R Core Team, 2023). Soil metrics were further condensed into a single variable using principal components analysis (PCA) with the function *prcomp* from the stats package (R Core Team, 2023). Significant differences in groupings based on Euclidean distances were evaluated using PERMANOVA with the *adonis2* function from the *vegan* package (Oksanen et al., 2022).

3 | RESULTS AND DISCUSSION

3.1 | Germination

Germination percentages were high for all ratios of agricultural soil to dredged sediments (>80%; Table S1). There was no significant effect of the ratio of agricultural soil to dredged sediments on the germination rate for corn ($p = 0.16$) or tall fescue ($p = 0.99$). However, canola in the 100% dredged sediment treatment germinated at a significantly slower rate than all other ratios ($T = 0.2521$, $p = 0.005$). Our germination rates fell within the expected range for the region. For example, emergence rates recorded for corn in the North Central and Northeastern Ohio region ranged from 97% to 86% with an average of 94% across 38 different hybrid varieties (Minyo & Geyer, 2021), which was consistent with our range of 100%–80% across ratios (Table S1). This suggests that the minimal variation we see in germination is reflective of natural variation in corn germination and not from the use of dredged sediments, cementing the idea that dredged sediments are an appropriate amendment to improve plant performance in Ohio soils.

3.2 | Corn

The ratio of agricultural soil to dredged sediments significantly altered corn performance for several growth metrics.

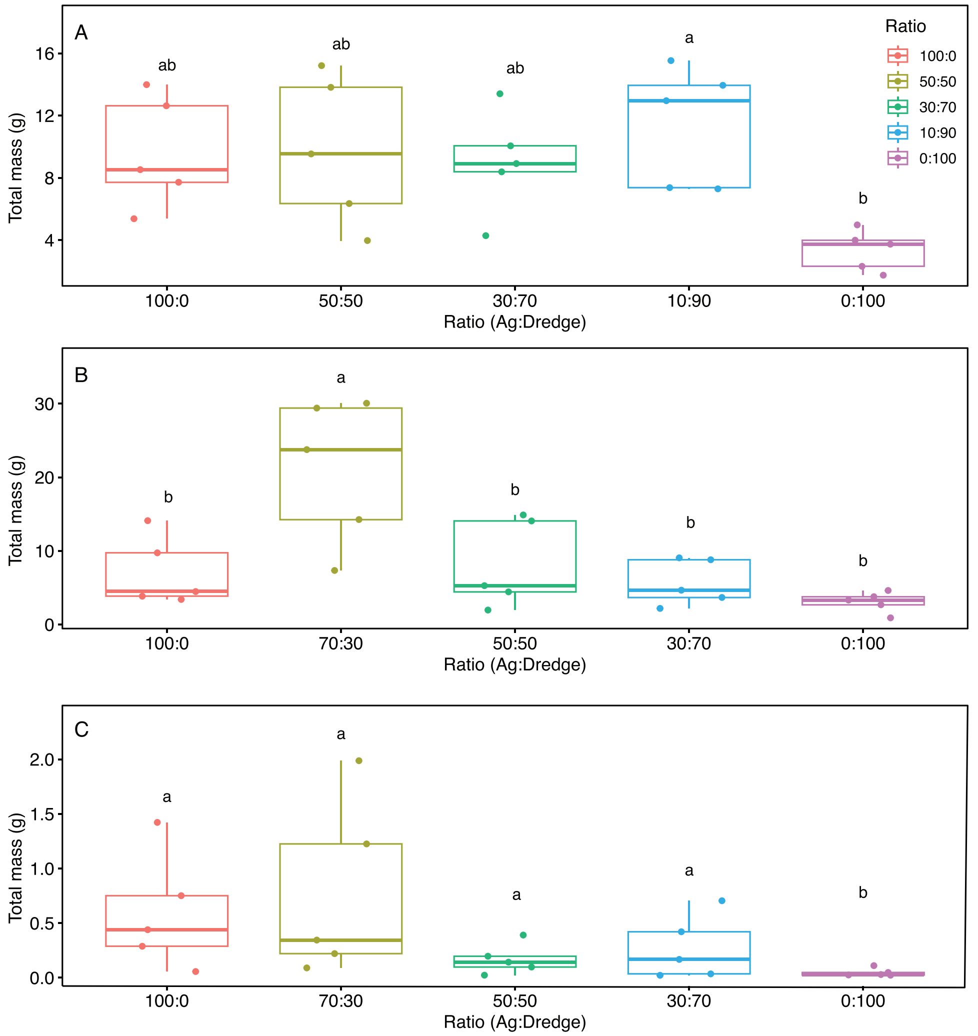

FIGURE 1 Plant mass (lbs) at harvest for (A) corn, (B) canola, and (C) tall fescue when grown on different ratios of agricultural soil to dredged sediments. Letters indicate significant differences in means as evaluated by Tukey's Honest Significant Difference (HSD). Points represent single plants and are jittered to not plot on top of one another.

There were significant differences in final plant biomass among ratios of agricultural soil to dredged sediments ($p = 0.0102$, $F_{4,16} = 4.755$) such that plants grown in 100% dredged sediments were smaller than all other treatments; however, that relationship was only significant for corn grown on agricultural soils supplemented with 90% dredged sediments (Figure 1A). Similarly, compared to any of the amended treatments, corn grew significantly shorter in the 100% dredged sediments starting at 43 days post germination and continuing throughout the growing period ($p = 0.0002$, $F_{4,460} = 5.547$; Figure 2A). This pattern was particularly striking for final height; plants in 100% dredged sediments were ∼8.6 times smaller than those in dredged sediment-supplemented treatments ($p < 0.0001$, $F_{4,20} = 24.37$; Figure 2B). While corn grown in the 100% dredged sediment treatment fared the worst, the 10% agricultural soil to 90% dredged sediment corn did just as well as the other application ratios.

The corn grown in this experiment was overall shorter than corn grown in the field. Corn height is generally driven by genetics; however, temperature, water intake, and light interception by top leaves during the growing period can all affect height. The plants in this study all received supplemental water and light and were kept at a constant temperature; however, we see other physiological parameters (kernel production, see below) that were also impacted by potential deficits in light availability, suggesting insufficient light also contributed to shorter overall plant height. While these plants were overall shorter than field-grown corn on dredged sediments (Julian et al., 2023), they complemented previous greenhouse research with 100% dredged sediments from Toledo Harbor, where corn grown in 100% dredged sediments consistently performed poorer than all other ratios of agricultural soils to dredged sediments (Julian, 2023). Together, these results suggest that even high applications of dredged sediments from Lake Erie harbors to Ohio agricultural soils can

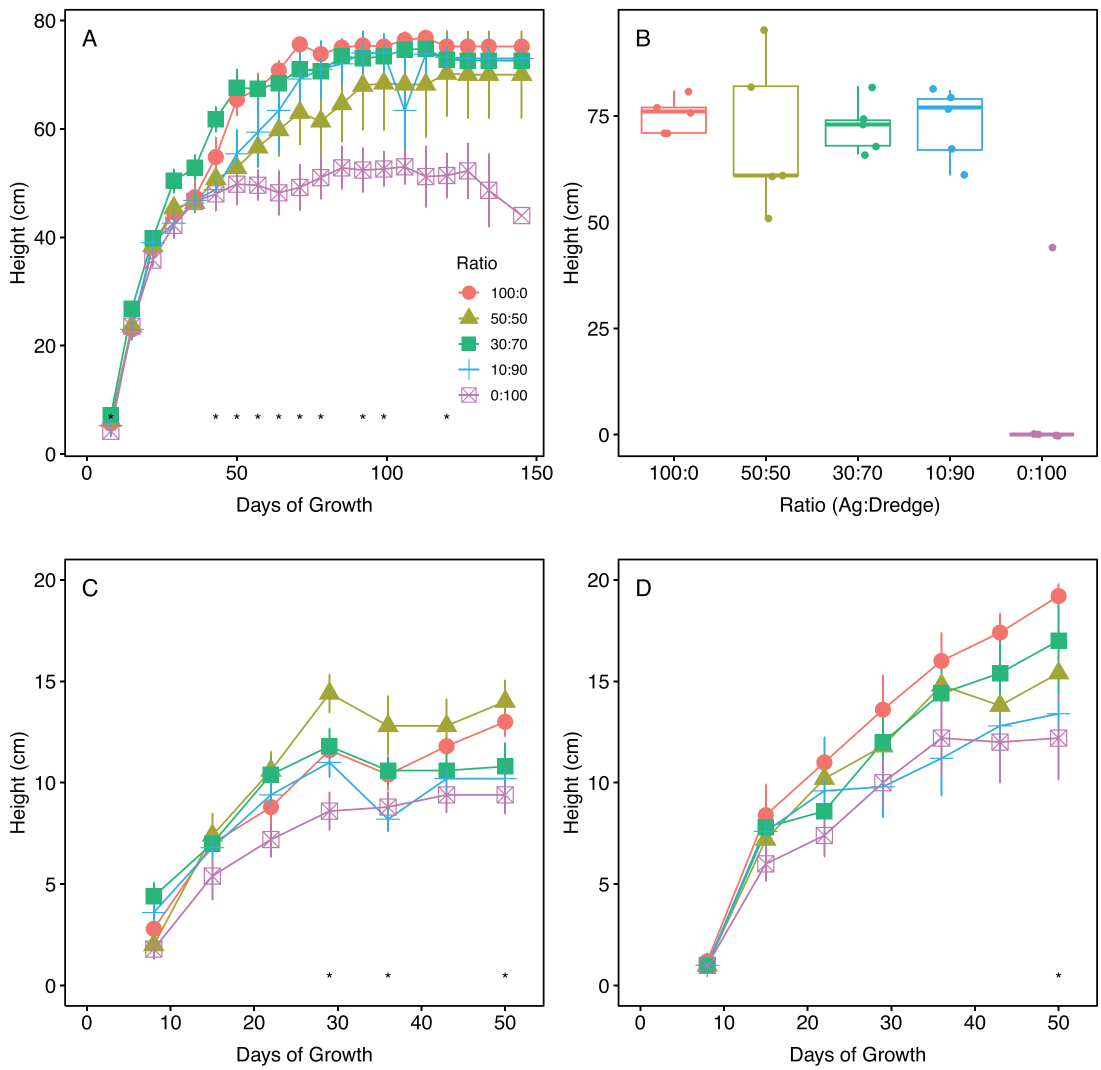

FIGURE 2 Plant height (in.) for corn (A), canola (C), and tall fescue (D) by days of growth since planting and for corn measured during final harvest at 145 days (B) when grown on different ratios of agricultural soil to dredged sediments. Significant differences among treatments for each growing day were determined with a Wilcox test. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ****$p < 0.0001$. Points for final height represent single plants and are jittered to not plot on top of one another, while all other points represent average height by day of growth.

TABLE 1 Average number of ears and tillers and standard deviation for plants grown on different ratios of agricultural soil to dredged sediments.

		Ratio					
	***p*-value**	**100:0**	**70:30**	**50:50**	**30:70**	**10:90**	**0:100**
Ears	0.0073	1.8 ± 0.84a	–	1.6 ± 1.1a	1.4 ± 0.55a	1.4 ± 0.55a	0.2 ± 0.45b
Tillers	0.0218	0 ± 0.0a	1 ± 0.71b	0.2 ± 0.45a	0.4 ± 0.9a	–	0 ± 0a

Note: $N = 5$ for all ratios. p-values are calculated based on an asymptotic chi square statistic based on the deviance of a generalized model with Gaussian fit. Letters indicate treatment differences based on least significant difference.

result in successful corn growth as long as there is a small percentage of agricultural soil initially present.

The number of corn ears produced varied significantly by the ratio of agricultural soil to dredged sediments ($p = 0.0073$, $\chi = 14$). Plants achieved between one and three ears for all treatments except 100% dredged sediments, which produced zero to one ear (Table 1). Hybrid corn has been developed to typically produce one to two ears per plant, so the fact that corn grown on dredged sediments, particularly those in high ratios (Table 1; 50% agricultural soil to 50% dredged sediments), produced three ears of corn demonstrates this growing environment was particularly beneficial for increasing overall yield. However, despite evidence of silking for all ears, none of the ears produced kernels. Unfortunately, this is not uncommon for greenhouse-grown corn, which can receive much lower light intensity than field-grown corn (Eddy & Hahn, 2010). While corn grown in this study did receive supplemental lighting, it may not have been at high enough intensity or for a long enough photoperiod to induce kernel production. However, previous research with corn grown on dredged sediments also suggested that it grows well on dredged sediments (Daniels et al., 2007; Darmody & Diaz, 2017; Lembke et al., 1983), even 100% dredged sediments from the Toledo Harbor (Julian et al., 2023). For example, corn grown on 100% dredged sediments produced more ears, more kernels per ear, and kernels with greater weight than other corn plants grown on traditionally farmed agricultural soils in Lucas County (Julian, 2023). Consequently, sediments from both the Toledo Harbor and Lorain Harbor, regardless of application ratio, increased both plant performance and yield, suggesting that corn growth benefits from the application of sediments dredged from any Lake Erie harbor source.

3.3 | Canola

Canola is increasingly planted in Ohio as a cover crop due to its ability to grow fast, scavenge nitrogen (N), reduce erosion and weed growth, and for forage and grazing (Ohio State University Extension, 2023). Consequently, understanding how dredged sediments alter canola performance is important for regional farmers. Both biomass ($p < 0.0001$, $F_{4,16} = 9.718$) and height ($p = 0.0102$, $F_{4,145} = 3.439$) changed due to the ratio of agricultural soil to dredged sediments. Plants grown in 70% agricultural soil to 30% dredged sediments had more mass (Figure 1B) and were taller (Figure 2C) than all other treatments, while plants were shortest throughout their growing period in the 100% dredged sediments (Figure 2C). These results indicate that canola growth is largely unaffected by the use of dredged sediments, barring the 70% agricultural soil to 30% dredged sediments treatment, which maximized both canola biomass and height. Consequently, growing canola on soils amended with dredged sediments will not have a negative effect on plant growth and may actually be beneficial when used in certain ratios. To our knowledge, this study is the first to examine the response of canola to dredged sediments application in any context.

3.4 | Tall fescue

Tall fescue represents one of the top three cool-season grasses produced in the United States (Christians et al., 2017), and its success is important to the turf grass industry in Ohio. Only a few metrics of plant performance for tall fescue were significantly affected by the ratio of agricultural soil to dredged sediments. While the final biomass of tall fescue did not significantly differ by the ratio of agricultural soil to dredged sediments ($p = 0.1056$, $F_{4,16} = 2.282$; Figure 1C), the number of tillers produced differed such that plants in the 70% agricultural soil to 30% dredged sediment treatment produced the most tillers ($p = 0.0218$, $\chi = 11.47$; Table 1). This may seem incongruous with expected results as an increase in tiller number is generally associated with an increase in biomass; however, in this study, not all plants reached the tillering stage prior to harvest, allowing the 70% agricultural soil to 30% dredged sediments treatment to drive the overall pattern in tiller numbers since it contained the highest proportion of plants that reached the tillering stage. Additionally, plant C:N ratio is generally thought to drive tiller initiation where greater available C leads to more tillering (Irving, 2015), so the results demonstrated here encourage the idea that the 70% agricultural soil to 30% dredged sediment treatment provided the best C:N ratio for overall tall fescue growth.

The ratio of agricultural soil to dredged sediments also significantly predicted plant height ($p = 0.0056$, $F_{4,145} = 3.812$) with the tallest plants in the 100% agricultural soil treatment and the shortest in the 100% dredged sediments throughout the growth period (Figure 2D). This suggests tall fescue grown in dredged sediments benefits from agricultural soils; however, a longer experiment may be necessary to fully understand the effect of dredged sediments on tall fescue performance compared to growth in agricultural soils alone.

3.5 | Soil properties

Conductivity, moisture, bulk density, and all three measures of soil texture (% sand, % silt, and % clay) all changed significantly from the beginning to the end of the experiment ($p < 0.0001$), although this effect was only captured in the 100% agricultural soils and 100% dredged sediments. These changes likely reflect the presence of the plant in these sediments and/or a continuation of the weathering process, particularly for the ratios highest in dredged sediment composition as the weathering process can continue during the first growing season (see Julian, 2023). Soil properties at harvest were remarkably similar across agricultural soil:dredged sediment ratios with 70:30, 50:50, 30:70, and 10:90 ratios representing intermediate values between 100% agricultural soil and 100% dredged sediments for conductivity, moisture, and all three soil texture values ($p < 0.0001$; Table 2). However, we failed to detect significant differences in soil compaction, pH, or BD among the treatments (Table 2). This likely reflects similar values between the 100% agricultural soil and 100% dredged sediment treatments for pH and BD and identical compaction values of low compaction (green < 200 psi) for all experimental units. Significance patterns mimic other

TABLE 2 Average soil property value and standard deviation for plants grown on different ratios of agricultural soil to dredged sediments.

Ratio	*N*	pH	Conductivity	Moisture	Bulk density	% Sand	% Silt	% Clay
p value		0.0767	**<0.0001**	**<0.0001**	0.3946	**<0.0001**	**<0.0001**	**<0.0001**
100:0	29	6.35 ± 0.46	789 ± 341ac	8.16 ± 7.01ac	0.878 ± 0.29	62 ± 0.13a	22 ± 0.07a	16 ± 0.11a
70:30	20	6.48 ± 0.42	1001 ± 355ab	10.5 ± 9.15ab	0.754 ± 0.31	65 ± 0.12a	19 ± 0.06a	16 ± 0.1a
50:50	20	6.64 ± 0.48	766 ± 811ac	15.7 ± 6.72ac	0.816 ± 0.24	55 ± 0.18ab	18 ± 0.06a	27 ± 0.15bc
30:70	30	6.53 ± 0.45	530 ± 533cd	17.3 ± 4.43cd	0.774 ± 0.18	48 ± 0.16bc	20 ± 0.04a	32 ± 0.14b
10:90	10	6.32 ± 0.47	1409.8 ± 589b	11.6 ± 9.47b	0.839 ± 0.22	66 ± 0.14a	17 ± 0.05a	45 ± 0.12b
0:100	30	6.61 ± 0.51	324 ± 280d	6.07 ± 3.69d	0.893 ± 0.22	32 ± 0.14b	17 ± 0.12b	13 ± 0.09a

Note: *N* values indicate the number of samples per ratio. *p*-values are calculated based on the main effect of ratio in a model including the interaction of ratio and collection time in a mixed effect model with block as a random effect. Significant values are in bold text. Letters indicate treatment differences based on Tukey's Honest Significant Difference (HSD).

greenhouse work with Lake Erie dredged sediments from the Toledo Harbor, which also showed intermediate values of soil properties collected from mixes of agricultural soil and dredged sediments (Julian, 2023). While permutational tests suggest soil property values grouped significantly by agricultural soil:dredged sediment ratio ($F_{5,35} = 10.54$, $p = 0.001$), these groupings were not visually distinctive (Figure S1), suggesting a large degree of variation and overlap in the recorded values for each ratio.

Despite the fact that several properties differed significantly among the agricultural soil:dredged sediment ratios (Table 2) and several metrics of plant performance (i.e., total biomass, height, tiller production, number of ears, etc.) were affected by the ratios, no soil properties consistently interacted with agricultural soil:dredged sediment ratio to alter plant biomass. While pH significantly interacted with agricultural soil:dredged sediment ratio to drive differences in corn biomass ($F_{4,15} = 4.161$, $p = 0.0183$), this was not true for either canola ($p = 0.5839$) or tall fescue ($p = 0.9394$). Similarly, the percentage of silt significantly interacted with agricultural soil:dredged sediment ratio to alter total biomass of tall fescue ($F_{4,14} = 4.786$, $p = 0.0121$), but neither canola ($p = 0.8860$) nor corn ($p = 0.4944$) experienced the same effect. No other soil properties significantly interacted with agricultural soil:dredged sediment ratio to alter corn or tall fescue biomass ($p > 0.05$), and canola biomass failed to be changed by any soil property at all, suggesting any significant differences in biomass due to agricultural soil:dredged sediment ratio reflect properties that we did not measure. In particular, soil nutrients like C, N, or P may be responsible for driving these patterns; however, if C were driving these patterns, we would expect properties like bulk density to significantly predict at least some of the variation in plant biomass (Lal & Kimble, 2000), which we failed to identify here. Alternatively, dredged sediments contain microorganisms responsible for nutrient cycling (Baniulyte et al., 2009; Kelly et al., 2007), and this is particularly true for dredged sediments from the Toledo Harbor, which also contain mycorrhizal fungi that are vital for plant growth (Rúa et al., 2023). Consequently, it is possible that certain ratios of agricultural soil:dredged sediments contain a greater portion of beneficial microorganisms (or a greater portion of detrimental microorganisms), and that may explain variation in our plant responses better than soil properties. Future research seeking to identify factors that are responsible for driving plant responses to dredged sediment applications when they are used as a soil amendment should consider not only changes in soil physiochemical properties but also microorganism responses.

4 | CONCLUSION

Overall, dredged sediments from the Lorain Harbor provided an excellent medium for plant growth. This was particularly true when used in combination with agricultural soil from traditionally farmed environments, which consistently outperformed the 100% dredged sediment treatments. While there are times when dredged sediments may be applied as the sole soil media, such as during restorations (Roddy et al., 2023), it is more likely that applications will occur to existing soil matrices. Understanding the ability of these applications to improve plant performance on such media is vital for understanding their ultimate success. One of the key indicators of success for applying dredged sediments to agricultural soils is plant reproductive ability. Our results suggest that corn grown on agricultural soil supplemented with dredged sediments produced additional ears and reached reproductive stages faster than corn grown solely on agricultural soil. Similarly, tall fescue produced more tillers when grown in agricultural soil supplemented with dredged sediments. In whole, outcomes from this study contribute to a growing body of research supporting the use of dredged sediments as a soil amendment for agricultural soils in Ohio (Brigham et al., 2021; Julian, 2023; Julian et al., 2023). While promising, future studies with dredged sediments from the Lorain

Harbor in the field are needed to fully understand the potential for these sediments to be used as a soil amendment.

AUTHOR CONTRIBUTIONS

Maureen E. Roddy: Data curation; investigation; methodology; writing—review and editing. **Emily Kalhert**: Investigation; methodology; writing—review and editing. **Corry T. Platt**: Conceptualization; writing—review and editing. **Ashley N. Julian**: Methodology; project administration; writing—review and editing. **Megan A. Rúa**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

During the course of the experiment, Corry T. Platt was employed by Coldwater Consulting, LLC who distributed funds to Dr. Megan A. Rúa to run the experiment with her team at Wright State University. While Mr. Platt participated in the initial experimental design and gave feedback on the final version of the manuscript, he did not collect the data, analyze the data, or compose the initial report.

DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during this study are available in the supplement and per request.

ORCID

Ashley N. Julian https://orcid.org/0009-0007-6805-7440
Megan A. Rúa https://orcid.org/0000-0002-2883-2795

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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