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Assessing the effect of Lake Erie dredged sediment on soil properties and specialty crops development

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Abstract

To maintain harbour navigability, significant quantities of sediments are annually dredged and disposed of in the vicinities of Lake Erie. This study aimed to assess the impact of Lake Erie sediment on the productivity of tomatoes, lettuce, and carrots. Using a greenhouse setting, this experiment evaluates different sediment-farm soil ratios: 100% farm soil (Farm Soil), 100% lake sediment (Sediment), and a blend of 10% dredge sediment and 90% farm soil (Mixture). We evaluated the chemical and physical composition of the treatments and the development of the roots, leaves, and fruit production for each crop. Additionally, Total Organic Carbon (TOC), Total Nitrogen (TN), and Total Phosphorus (TP) were assessed post-harvest for each crop's roots, leaves, and fruit biomass. The Sediment treatment showed higher pH, Cation Exchange Capacity (CEC), Calcium, and TOC but lower magnesium, phosphate, and potassium compared to Farm Soil. The Sediment and Mixture treatments exhibited higher root and leaf dry weights for lettuce compared to Farm Soil, with the Sediment treatment showing the longest roots. Sediment and Mixture treatments in carrots led to greater root weight and length. Tomatoes submitted to the Sediment treatment excelled in all variables except stem diameter. Lettuce and carrot biomass analysis revealed no statistical differences in TOC and TN among the treatments. Tomato biomass analysis showed no differences among the three treatments. The use of Lake Erie dredged sediment led to increased crop biomass in the greenhouse production of tomatoes, carrots, and lettuce.

KEYWORDS

lake dredged sediment, plant development, soil properties, specialty crop

1 | INTRODUCTION

The Great Lakes of North America comprise the Superior, Michigan, Huron, Erie, and Ontario Lakes. Together, these lakes form the largest freshwater surface system globally (Great Lakes Commission, 2021). Over one-third of the entire Great Lakes basin population – 11.6 million people – reside within the Lake

Erie watershed. Lake Erie plays a crucial role, offering significant natural, economic, and recreational benefits, contributing $12.9 billion to tourism annually (Bhairappanavar et al., 2018). However, Lake Erie faces substantial pressures from urbanization, industrialization, and agriculture, surpassing other Great Lakes in the quantity of effluent from sewage treatment plants. It also experiences the highest sediment loading, influenced by underlying geology and land use patterns. Regions in southwest Ontario and northwest Ohio, characterized by exposed agricultural and urban lands, significantly contribute to sediment loads in the Lake (French et al., 2011).

As a result, the Army Corps of Engineers undertakes an annual dredging effort to maintain the navigability of the ships through the federal navigational channels. This process involves removing ca. 1.5 million tons of sediment from the Lake bed. Traditionally, the dredged material was either deposited in the open waters of Lake Erie or allocated in designated confined areas (Brandon & Price, 2007; Liu et al., 2019; Moog et al., 2018). However, the practice of open-water disposal results in nutrient redistribution, increases the risk of harmful algal blooms, and releases organometallic components if present (Bhairappanavar et al., 2018; Truitt, 1988). Due to the negative impact on water quality, the disposal of dredged sediment from Toledo Harbour into the open waters of Lake Erie is prohibited since July 1, 2020 (Gardner & Peterson, 2015; Ohio Lake Erie Commission, 2021; Ohio Revised Code, 2015). The urgency of finding a sustainable solution to this issue is evident.

The Lake Erie dredged material is currently deposited in designated confined areas. However, this disposal method is not free of environmental and economic impacts. Depositing the sediment in confined areas has been reported to cause leachate to permeate the underlying soil and enter the groundwater (Bhairappanavar et al., 2018; Chen et al., 1978; Truitt, 1988). Additionally, the substantial amount of dredged sediment generated annually necessitates the identification of new confined areas, which is often hindered by urbanization in the surrounding regions, resulting in increased costs and logistical challenges (Brandon & Price, 2007; Liu & Coffman, 2016). Given the accumulation of dredged sediment and its associated challenges, it is crucial to explore reuse alternatives. One potential application is to amend farm soils, a practice previously employed in agriculture to improve the productivity of crops (Bhairappanavar et al., 2018; Brigham et al., 2021).

Previous research suggests that dredged sediments can enhance plant productivity by improving the chemical and physical characteristics of marginal soils (Liu et al., 2019). Studies conducted in Gonghu Bay, China, have found that utilizing dredged sediment can contribute to restoring urban riverbank ecosystems (Huang et al., 2019). Researchers observed that the dredged sediment from Gonghu Bay had a higher organic matter content, which resulted in improved plant growth compared to areas where sediment was not applied (Huang et al., 2019). Furthermore, a recent study examined the impact of Lake Erie dredged sediments on soybean plants cultivated under protection (Brigham et al., 2021). The findings revealed that dredged sediments improve the overall development of soybean plants, surpassing the growth observed in regular farm soil or soil with a low sediment content. The study also found that the increased sediment content positively influenced various soil properties. Specifically, it resulted in increased Calcium (Ca) concentration, higher Cation Exchange Capacity (CEC), higher organic carbon content, and reduced bulk density (Brigham et al., 2021). Additionally, studies using sediments extracted from different water bodies have reported increased water-holding capacity and improved macro and micronutrient availability, resulting in better crop development (Daniels et al., 2007; Darmody & Marlin, 2002; Develioglu & Pulat, 2017; Ebbs, 2006).

While previous studies have examined the performance of specialty crops using dredged sediment (Daniels et al., 2007; Darmody & Marlin, 2002; Develioglu & Pulat, 2017; Ebbs, 2006), there is a lack of research on the effects of Lake Erie's dredged sediment specifically on tomatoes, carrots, and lettuces. The existing findings and identified research gaps served as the foundation for conducting this study. We aim to assess the impact of dredged sediment from the Toledo Harbour on soil properties and specialty crop development by comparing agronomical measures and biomass analytical results of plants submitted to varying substrate treatments in a controlled greenhouse environment. More specifically, we assessed the soil treatments' physical and chemical properties, selected agronomical parameters, and the concentrations of Total Organic Carbon (TOC), Total Nitrogen (TN), and Total Phosphorus (TP) in roots, leaves, and fruits.

With our research objective in mind, we hold the hypothesis that the application of dredged sediment positively influences soil properties, enhances the production of edible tissues, and increases the overall biomass development of cultivated plants. This research, therefore, contributes significantly to understanding the potential benefits and implications of utilizing Lake Erie dredged sediment in specialty crop production, offering a promising solution to local challenges.

2 | MATERIALS AND METHODS

2.1 | Study site description

Toledo, Ohio, experiences its warmest months between May and September, with an average daily high temperature of 23°C. The hottest days of the year are in July when the average high is ca. 28°C with a low of 18°C. The coldest months range between December and March, with an average daily high temperature below 6°C. The coldest days of the year are between January and February, with an average low of −7°C and a high of 0°C. In 2022, the total annual precipitation in Toledo added to 798 mm. The highest precipitation occurred in August, reaching 105 mm, while the lowest was recorded in January, with 16 mm (Source: National Weather Service, Express AP station).

The soil used in the greenhouse experiment was collected from a community garden located at the Agriculture Incubator Foundation, Bowling Green, Ohio. The soil belongs to the Hoytville series (family fine, illitic mesic *Mollic Epiaqualfs*). Dredged sediment was provided by the Great Lakes Dredge Material Center for Innovation (GLDMCI). The GLDMCI was created by the Toledo-Lucas County Port Authority to study the possible beneficial uses of dredged sediment in agriculture. Sediments from the GLDMCI were allowed to dewater for 2 years via drainage tiles before being used in our experiment (Hull & Associates Inc., 2018). The dredged material is comprised of ca. 70% to 98% silt and clay, and the remaining is sand. The percentage difference is most likely based on the collection locations from the upper river channel and lower river channel (i.e., 74.9% silt/clay and 98.8% silt/clay, respectively) (USACE, 2009). Regarding the farm soil, 36% of the material is clay, 37% is sand, and the remaining is silt. The total amount of dredged material deposited on the GLDMCI site was 30,800 and 26,923 cubic meters in 2016 and 2017, respectively (Hull & Associates, 2018). Farm soil and dredged sediments were collected in January 2022.

2.2 | Dredged sediment and farm soil collection

The farm soil and dredged sediments were collected from the surface layer (upper 30 cm) and transported via a dump truck to a secure, covered storage area at the Agricultural Incubator Foundation Center for air-drying, as illustrated in Figure S1. The controlled air-drying process reduced water content and adhesiveness, facilitating subsequent manual fragmentation and homogenization of the solid materials. For the homogenization process, air-dried solids were piled into the center of a plastic tarp, and the soil was carefully raked, as depicted in Figure S2. This approach ensured a consistent and representative composition. Subsequently, samples of both farm soil and dredged material were collected and stored at room temperature for further characterization. This analysis phase was denoted as the "time zero solid characterization."

2.3 | Greenhouse setup and harvesting

This study evaluated the chemical and physical properties of the soil and nutrient content, growth, and agronomic performance of three crop varieties: Outredgeous Romaine lettuce (*Lactuca sativa* L.), Mokum carrots (*Daucus carota* L.), and BHN 589 tomatoes (*Solanum lycopersicum* L.). The crops were cultivated under three distinct treatments with varying ratios of Lake Erie sediment and farm soil. The ratios were 100% Lake Erie dredged sediment (Sediment), 100% farm soil (Farm Soil), and a mixture of 90% farm soil and 10% Lake Erie dredged sediment (Mixture). We determined the Mixture treatment ratio based on recommendations from Brigham et al. (2021). To facilitate a comprehensive analysis, a Randomized Complete Block Design was implemented. The experimental design consisted of four blocks, with three treatment groups, resulting in 12 experimental units. Each experimental unit comprised five plants, which were sown in 5-gallon plastic buckets, amounting to 60 plants per crop distributed across the experimental design (Figure S3).

To ensure uniformity, the farm soil and sediments were separately homogenized inside the greenhouse facility using a shovel, resulting in two consistent media. For the mixture treatment, we prepared a blend of 90% soil and 10% sediment by volume. Once the treatments were adequately homogenized, 1 kg samples were prepared and sent for physical and chemical analysis. This analysis determined the pH, CEC, Ca, Magnesium (Mg), Phosphate (PO_4^{3-}), Potassium (K), and TOC for each sample, along with assessing the treatment textures and bulk density. The analytical methods employed conventional soil test procedures: pH was determined using the 1:1 deionized water to soil method; CEC was estimated by summing the cations extracted using regular soil tests and accounting for the soil's exchangeable acidity; the values for Ca, Mg, PO_4^{3-} and K utilized the Mehlich III method.

Subsequently, the 5-gallon buckets were filled with the appropriate treatment media or blend and irrigated. The buckets were then placed in their respective blocks for a one-week acclimation period. During the acclimation period, we proceeded with planting and nurturing the lettuce and tomato seedlings in preparation for their transplantation into the designated buckets. Lettuce and tomato seeds were sown in trays containing 128 cells, each cell measuring 1.2 inches in diameter and 1.8 inches in depth. The Pro-Mix Premium Organic Vegetable & Herb Mix was utilized as the growing media. One seed of tomato and lettuce was individually planted in each tray cell. After a period of 30 days, the tomato and lettuce seedlings were transplanted into the 5-gallon buckets filled with the respective treatment media. In the case of the carrots, the seeds were directly sown into the 5-gallon buckets containing the designated treatment substrates.

Throughout the experiment, all crops grown in the greenhouse were managed by daily manual watering, ensuring that the treatment buckets maintained humidity above 40% of the available water capacity. Our irrigation protocol was based on practical extension publications (Grattan & Oster, 2003; Sharma, 2019) and tensiometer measures. Synthetic fertilizers or pesticides were not applied at any point during the study. The temperature within the greenhouse was regulated by a heating, ventilation, and air conditioning (HVAC) system. The system included a heater, a cooling wall, exhaust fans, circulation fans, and roof vents, capable of maintaining a favourable temperature range between 24 and 29°C (Figures S4, S5). The temperature was maintained to provide optimal growing conditions for the crops under investigation. The greenhouse did not have curtains.

On day 35 after transplantation, we harvested the lettuce plants (Figure S6). We cut the plants at the intersection of the stem and the roots using scissors (Figure S7). We thoroughly washed and cleaned the aboveground and belowground biomass to remove any substrate residue. Each section of the plant was then individually weighed using a digital scale with an accuracy of 0.01 g. After weighing the aboveground and belowground parts, we measured the root length using a ruler to obtain additional morphological data. Subsequently, we placed the aboveground and belowground biomass in separate paper bags and placed them into an oven set at 60°C. The samples were dried until a constant weight, indicating the complete removal of moisture. This ensured accurate dry biomass measurement and comparison among the different treatments.

The carrots were ready for harvest 55 days after sowing (Figure S6). Prior to measurements, the harvested carrots were thoroughly washed and cleaned to eliminate any substrate particles, and the foliar section of each carrot was removed. To determine the length of the carrots, we used a ruler to measure the distance from the root crown to the root tip, excluding the etiolated portion of the root (Figure S8). Using a calliper, we measured the width of the carrots below the root crown. This provided an accurate assessment of the carrot's diameter at a specific point. To obtain the fresh weight of the carrots, we placed the carrots on a digital scale with an accuracy of 0.01 g.

We harvested the tomato fruits on days 75, 79, and 83 after transplanting (Figure S6). We waited until the fruit reached full reddish coloration and recorded the number of harvested fruits. After a total of 90 days, we also measured the stem diameter and plant height of each tomato plant. The plant height was determined using a long ruler, while the stem diameter was measured using a calliper. We took the diameter measurements at the base of the plant, in the first section above the soil. To prepare the plants for measurement, we carefully cut them at the intersection of the roots and the foliar section using scissors. Then we washed the roots thoroughly to remove the media (Figure S9). After washing, we weighed the roots individually using a digital scale with an accuracy of 0.01 g. The lettuce leaves, carrots, and tomatoes were freeze-dried and pulverized for later TOC, TN, and TP analysis. Air-dried and freeze-dried biomass samples were crushed using a Glen Mills Labtechnics Pulverizer to 75 μm.

2.4 | Analytical methods

A solid-phase physicochemical characterization was conducted twice during the project for the different compositions of soil and dredged sediments. The initial characterization was done at time zero. The second characterization was done immediately after harvesting each crop. Soil core samples were collected to a depth of 15 cm, placed in plastic bags, and then air-dried under a fume hood. All soils were crushed using a Glen Mills Labtechnics Pulverizer to 75 microns. Total Carbon, TOC, and Total Inorganic Carbon (TIC) content were determined using high-temperature oxidation followed by infrared detection of CO_2 (Shimadzu TOC-VCSH equipped with a solid sample module, Shimadzu SSM-5000A). TN and TP were analyzed using the alkaline persulfate digestion method, followed by colorimetric detection using a Seal AQ2 Discrete Analyzer (Patton & Kryskalla, 2003). Although this method was originally designed for water samples, its application for soil and organic matter has been demonstrated to produce valid and accurate results (Berthold et al., 2015; Gibson et al., 2015; Purcell & King, 1996; Smart et al., 1983; Studt et al., 2020). The alkaline persulfate digestion is a superior method to its alternatives (e.g., dichromate and Kjeldahl digestions) as it uses less environmentally harmful and toxic agents. The alkaline persulfate digestion solubilizes a wider range of P and N components than digestions involving only acidic or alkaline solutions. The strongly oxidizing conditions produced by the homolysis of the peroxide bond in persulfate promote digestion and dissolution of recalcitrant materials, enhancing the detection of the total amount of phosphorus and nitrogen present in the material. Because of the nature of soils and plant tissues, variance tends to be higher than with water samples but frequently lower than 20% when homogeneous soil or plant tissue materials are used. Further description of the alkaline persulfate method using soil and plant samples can be found in the literature cited. TOC, TN, and TP contents in biomass samples were determined using the same methods described above. The hydrometer method (Waypoint Analytical Laboratories) determined the particle size analysis for the treatments. For bulk density analysis, an additional core sample was oven-dried at 105°C until the weight was constant and recorded.

2.5 | Statistical analyses

The data analysis was performed using the PROC MIXED procedure of the Statistical Analysis System, SAS® version 9.4. Two procedures were executed to assess normality. First, the Shapiro–Wilk test with a significance level of 0.05 was conducted based on the observed data. Secondly, we estimated the analysis of variance (ANOVA) residuals and re-assessed normality following Kozak and Piepho (2017). The second procedure provides more accurate results due to a larger sample size and because the dependent variables within treatments are examined jointly. Results showed that not all variables of interest followed a normal distribution. To normalize the data, we square root transformed the variables that failed the preliminary analyses and executed the procedures again. The required normality assumptions for a proper ANOVA were met after the transformations. Specific details on data transformations are provided in table footnotes (Tables S1–S3). The transformed variables were back-transformed to present results on treatment differences. To further investigate pairwise differences between treatment means, we conducted mean separations using the Tukey test at a significance level of $p \leq .05$.

3 | RESULTS

3.1 | Effect of dredged material on soil properties

The soil chemical analysis results revealed notable differences among the three treatments in time zero. The Sediment treatment exhibited higher pH, CEC, Ca, and TOC compared to the Farm Soil treatment. In contrast, Mg, PO_4^{3-}, and K content in the Sediment were lower compared to the Farm Soil treatment (Table 1).

TABLE 1 Soil analysis results with the average and standard deviation (in parenthesis) for all treatments at time zero and after harvesting.

		Meq/100g	mg kg^{-1}				
Treatment	**pH**	**CEC**	**Ca**	**Mg**	**PO_4^{3-}**	**K**	**TOC**
Time zero							
Farm soil	6.8	22.1	3420	467	71	234	25,561
Sediment	7.6	42.4	7682	418	69	189	29,213
After harvesting lettuce							
Farm soil	7.05^{c} (0.05)	20.9^{c} (1.30)	3246^{c} (219.35)	493^{a} (24.30)	66^{a} (19.00)	224^{a} (11.44)	28,792^{a} (2015)
Mixture	7.33^{b} (0.04)	25.6^{b} (2.53)	4260^{b} (481.70)	461^{a} (16.13)	67^{a} (7.82)	198^{a} (15.5)	27,546^{a} (2392)
Sediment	7.73^{a} (0.04)	37.6^{a} (1.36)	6674^{a} (212.86)	467^{a} (36.29)	63^{a} (1.47)	162^{b} (4.60)	27,415^{a} (1037)
After harvesting carrot							
Farm soil	7.45^{ab} (0.23)	25.2^{b} (2.29)	3934^{b} (440.67)	596^{ab} (47.67)	55^{a} (15.00)	237^{a} (19.09)	28,397^{a} (4971)
Mixture	7.23^{b} (0.08)	27.1^{b} (2.83)	4410^{b} (552.68)	549^{b} (13.49)	69^{a} (2.77)	193^{b} (8.86)	23,167^{a} (7729)
Sediment	7.70^{a} (0.10)	46.1^{a} (1.25)	8062^{a} (236.88)	641^{a} (16.74)	75^{a} (2.94)	166^{b} (4.49)	26,858^{a} (750)
After harvesting tomato							
Farm soil	7.15^{c} (0.05)	20.5^{c} (0.91)	3074^{c} (127.68)	567^{b} (33.11)	63^{a} (8.75)	150^{a} (11.44)	23,733^{a} (770)
Mixture	7.38^{b} (0.08)	26.9^{b} (0.58)	4320^{b} (106.51)	592^{b} (14.83)	64^{a} (6.57)	154^{a} (6.44)	21,930^{a} (6154)
Sediment	7.78^{a} (0.043)	38.5^{a} (1.04)	6520^{a} (201.47)	673^{a} (8.21)	73^{a} (1.11)	125^{b} (3.03)	25,961^{a} (1074)

Note: Values are the means of four replicates. Means followed by distinct letters in the column are significantly different by the Tukey test at a 5% probability level. A&L Great Lakes Laboratories Inc. Farm Soil: 100% farm soil; Mixture: 90% farm soil and 10% Lake Erie dredged sediment; Sediment: 100% lake dredged sediment. For time zero, $n = 1$.

Abbreviations: CEC, cation exchange capacity; TOC, total organic content.

The chemical soil analyses were repeated after harvest and crop removal for each treatment. In the buckets where lettuce was cultivated, the Sediment treatment demonstrated statistically higher pH, CEC, and Ca concentrations compared to the Mixture and Farm Soil treatments. Conversely, the Farm Soil treatment yielded the lowest values for these three parameters. No statistical differences were observed for Mg, PO_4^{3-}, and TOC among the three treatments. Regarding K, the Sediment treatment was statistically lower compared to the Farm Soil and Mixture treatments after harvesting lettuce. No statistical difference was observed between the Farm Soil and Mixture for K.

In the carrots experiment, no statistical differences were found between the Sediment and Farm Soil treatments for pH, Mg, PO_4^{3-} and TOC, nor between the Farm Soil and Mixture. The Sediment treatment showed higher statistical values compared to the Mixture treatment for pH and Mg and equivalent values for PO_4^{3-} and TOC. The Sediment had statistically higher values for CEC and Ca than the Farm Soil and Mixture treatments, with no statistical difference between the latter two. As for K, the Farm Soil had higher values than the Sediment and Mixture, but no statistical difference was found between the Mixture and Farm Soil treatments.

In the case of tomato cultivation, the Sediment treatment exhibited higher statistical values for pH, CEC, Ca, and Mg compared to the Mixture and Farm Soil treatments. The Mixture had higher statistical values compared to Farm Soil for pH, CEC, and Ca, and equivalent Mg measures. Regarding K, Sediment had the lowest statistically significant measure compared to the other two treatments, whereas no statistical difference was observed between Farm Soil and Mixture treatments. The analysis returned no significant differences for PO_4^{3-} and TOC across all treatments.

The physical properties analysis conducted by Waypoint Analytical classified all treatments as 'Clay Loam' (Table S4). However, there were differences in the percentages of clay, silt, and sand. The Sediment treatment had a lower clay percentage and a higher silt percentage compared to the Mixture and Farm Soil. In contrast, the Farm Soil treatment exhibited a higher clay percentage but a lower sand percentage than the Sediment and Mixture treatments. As for the sand content, the Mixture had the highest percentage of sand. Regarding bulk density, the Sediment treatment had the lowest value compared to the Farm Soil and Mixture treatment. Although Farm Soil had the highest bulk density, no statistically significant differences were observed among the treatments (Table S5).

3.2 | Effect on the specialty crops

The lettuce plants cultivated in the Sediment treatment exhibited statistically higher root length (RL) and fresh root weight (FRW) measures compared to plants in the Mixture and Farm Soil treatments. No statistical differences were observed for RL and FRW between the Farm Soil and Mixture. Measures for fresh leaf weight (FLW), dry leaf weight (DLW), and dry root weight (DRW) behaved similarly. These three parameters for the lettuce grown in the Sediment and Mixture treatments were statistically higher compared to the Farm Soil treatment. There were no statistical differences between plants in the Sediment and Mixture treatments for these parameters. Results are summarized in Table 2.

For lettuce leaf analysis, TOC and TN showed no statistical differences among the three treatments. However, TP from the Mixture treatment was statistically higher compared to Farm Soil, while showing no statistical difference compared to Sediment. The Sediment treatment showed no statistical difference compared to Farm Soil for TP. For lettuce roots, there were no statistical differences among the treatments for TOC, TP, and TN. A comprehensive overview of these results can be found in Table 5.

The carrots experiment provides additional evidence of the positive effect of Lake Erie dredge sediments on crop performance. Carrot length (RL) was statistically higher in the Sediment treatment compared to Farm Soil, although there were no statistically significant differences between Sediment and Mixture or Mixture and Farm Soil. For fresh root weight (FRW), carrots from the Sediment treatment

TABLE 2 Significance for all treatment averages and standard deviation (in parenthesis) in the aboveground and belowground development of lettuce cv. Romaine.

Treatment	Root length (cm)	Fresh root weight (g)	Fresh leaf weight (g)	Dry leaf weight (g)	Dry root weight (g)
Farm Soil	5.8^b (0.7)	2.7^b (1.3)	28.8^b (10.7)	1.6^b (0.4)	0.2^b (0.1)
Mixture	5.8^b (0.9)	3.0^b (0.8)	41.5^a (9.3)	2.2^a (0.4)	0.3^a (0.3)
Sediment	6.9^a (0.9)	3.9^a (0.9)	38.3^a (9.9)	2.8^a (0.5)	0.3^a (0.4)

Note: Values are the means of four replicates. Means followed by distinct letters in the column are significantly different by the Tukey test at a 5% probability level. Farm Soil: 100% farm soil; Mixture: 90% farm soil and 10% Lake Erie dredged sediment; Sediment: 100% lake dredged sediment.

were statistically heavier compared to the Mixture and Farm Soil treatments. No statistical difference in FRW was observed between Mixture and Farm Soil. For carrot root diameter (RD), no statistical differences were observed between the treatments. Table 3 summarizes these findings.

The carrot biomass analyses returned no statistical differences for TOC and TN on the leaves and no statistical differences for TOC, TP, and TN on the roots. Statistical differences were limited to TP on the leaves. For the latter parameter, Farm Soil showed a statistically higher measure compared to Sediment. In contrast, no statistically significant differences were observed between Farm Soil and Mixture or between Mixture and Sediment. Table 5 reports these results.

For tomatoes, the Sediment treatment showed higher statistical means for FRW, stem height (SH), and the number of fruits (NF) compared to the Farm Soil and Mixture treatments. However, there was no statistical difference in SH and NF between Farm Soil and Mixture. The Mixture treatment exhibited a statistically higher FRW compared to the Farm Soil treatment. No significant difference was observed in stem diameter (SD) among the three treatments. These results are summarized in Table 4. The biomass analyses of tomato fruits, leaves, and roots revealed no statistical differences among the three treatments for all parameters analyzed (Table 5).

TABLE 3 Significance for all treatment averages and standard deviation (in parenthesis) in the agronomical development of carrot cv. Mokum.

Treatment	Root length (cm)	Fresh root weight (g)	Root diameter (cm)
Farm soil	8.6^{b} (1.3)	42.2^{b} (16.3)	0.9^{a} (0.3)
Mixture	9.2^{ab} (1.5)	44.7^{b} (19.8)	0.9^{a} (0.2)
Sediment	9.5^{a} (1.7)	60.9^{a} (22.7)	0.9^{a} (0.2)

Note: Values are the means of four replicates. Means followed by distinct letters in the column are significantly different by the Tukey test at a 5% probability level. Farm Soil: 100% farm soil; Mixture: 90% farm soil and 10% Lake Erie dredged sediment; Sediment: 100% lake dredged sediment.

4 | DISCUSSION

This study investigates the effects of Lake Erie dredged sediment on soil properties and specialty crop development parameters. The initial focus was to evaluate the physical and chemical soil composition of the treatments. Sequentially, we re-evaluated soil nutrient composition and crop development parameters, encompassing agronomical measures and biomass analyses.

Based on three independent crop experiments, results suggest that the use of sediments does not cause negative effects on soils. While the pre-planting chemical analysis returned an alkaline pH and lower Mg, PO_4^{3-}, and K concentrations in the Sediment treatment compared to Farm Soil, crop development was not negatively affected. The Sediment treatment analysis returned higher CEC, TOC, and Ca concentrations than the other two treatments, partially explaining the superior crop development in the former.

The agronomical results demonstrate that root parameters measured consistently higher in the presence of Lake Erie dredged sediments. Leaf parameters behaved similarly. To mention, root length (RL) and fresh root weight (FRW) for lettuce and carrots, FRW for tomatoes, and dry root weight (DRW) in the lettuce experiment returned superior and statistically significant measures in the Sediment treatment compared to Farm Soil. These measures in the Sediment treatments were also higher than those in the Mixture treatments, except for RL in the carrot and DRW in the lettuce experiments, where no statistically significant differences were observed. Regarding aboveground parameters, the Sediment treatment returned significantly higher measures for several parameters. Fresh and dry leaf weights in lettuce and stem height and fruit yield in tomatoes performed statistically better in the Sediment treatment than Farm Soil. Statistical differences between Sediment and Mixture were observed for two aboveground parameters in the tomato experiment.

A set of reasons may explain these findings. It is known that optimal crop development requires deep and loose soils (Phillips et al., 2022). Although all treatments were classified as 'Clay Loam,' the Sediment treatment

TABLE 4 Significance for all treatment averages and standard deviation (in parenthesis) in the agronomical development of tomato cv. BHN 589.

Treatment	Fresh root weight (g)	Stem height (cm)	Number of fruits	Stem diameter (cm)
Farm soil	4.3^{c} (1.1)	704.0^{b} (100.7)	15.5^{b} (3.8)	12.1^{a} (0.8)
Mixture	5.8^{b} (1.5)	677.0^{b} (65.6)	14.8^{b} (3.1)	12.4^{a} (1.7)
Sediment	11.9^{a} (1.8)	777.4^{a} (94.9)	23.8^{a} (4.0)	12.8^{a} (0.8)

Note: Values are the means of four replicates. Means followed by distinct letters in the column are significantly different by the Tukey test at a 5% probability level. Farm Soil: 100% farm soil; Mixture: 90% farm soil and 10% Lake Erie dredged sediment; Sediment: 100% lake dredged sediment.

TABLE 5 Biomass analysis results with the average and standard deviation (in parenthesis) for all treatments and crops after harvesting.

Treatment	TOC (g kg^{-1})	TP	TN	TOC (g kg^{-1})	TP	TN
	Lettuce					
	Leaves			**Roots**		
Farm soil	327.77^a (21.89)	2.45^b (0.52)	22.57^a (3.49)	375.05^a (8.56)	2.94^a (0.18)	15.74^a (1.15)
Mixture	316.73^a (31.72)	3.73^a (0.47)	24.11^a (3.58)	363.51^a (8.51)	2.95^a (0.07)	15.81^a (1.41)
Sediment	320.18^a (35.38)	3.22^{ab} (0.24)	28.81^a (3.18)	371.62^a (19.78)	3.06^a (0.12)	19.31^a (2.24)
	Carrots					
	Leaves			**Roots**		
Farm soil	339.77^a (4.92)	3.79^a (0.49)	18.22^a (1.44)	362.53^a (12.02)	4.33^a (0.60)	8.63^a (1.44)
Mixture	344.32^a (3.37)	3.17^{ab} (0.54)	17.84^a (0.58)	364.01^a (5.57)	4.60^a (0.20)	9.57^a (1.19)
Sediment	336.70^a (6.14)	2.38^b (0.38)	20.16^a (3.28)	366.37^a (8.25)	3.94^a (0.31)	9.90^a (0.50)
	Tomatoes					
	Leaves			**Roots**		
Farm soil	328.16^a (12.96)	12.68^a (2.16)	18.22^a (2.66)	339.16^a (14.07)	3.96^a (0.68)	12.24^a (0.90)
Mixture	333.37^a (8.11)	9.97^a (1.94)	16.41^a (3.15)	308.77^a (17.12)	3.98^a (0.50)	12.59^a (0.88)
Sediment	326.48^a (11.09)	10.57^a (0.77)	17.82^a (1.91)	312.44^a (22.79)	4.36^a (0.33)	13.21^a (0.55)
	Fruits					
Farm Soil	375.71^a (10.12)	4.53^a (0.12)	10.88^a (1.24)			
Mixture	370.47^a (6.28)	5.07^a (0.72)	10.13^a (1.90)			
Sediment	367.46^a (6.09)	4.45^a (0.34)	9.72^a (1.06)			

Note: Means followed by distinct letters in the column are significantly different by the Tukey test at a 5% probability level. Farm-soil: 100% farm soil; Mixture: 90% farm soil and 10% Lake Erie dredged sediment; Sediment; 100% lake dredged sediment.

Abbreviation: TOC, Total Organic Carbon; TP, Total Phosphorus; TN, Total Nitrogen.

had the lowest bulk density compared to the Farm Soil and Mixture treatments. While this may be related to the highest TOC measure before planting, the Sediment treatment also had lower clay and higher sand contents than the Farm Soil treatment. Soils with higher sand content typically have improved soil porosity and a greater number of macropores, responsible for improved soil aeration and unrestricted water flow (Hao et al., 2019; Pagliai & De Nobili, 1993). Moreover, the established literature explains that effective water movement in the soil is vital for nutrient transportation to plant roots, facilitating the dissolution and mobility of essential minerals, thereby enhancing plant accessibility to nutrients (Taiz et al., 2023).

The effects of TOC and soil nutrient content must be discussed further as plausible explanations for our results. Organic matter enhances soil structure and improves soil chemical properties (Lehmann & Kleber, 2015). A previous study with a 50% sediment and 5% biochar blend improved soil porosity, structure, phosphorus nutrition, and microbial diversity (Huang et al., 2019). Our results complement these and other research findings, which are discussed below. While dredged sediments and biochar improved P intake in Huang et al. (2019), the biomass analysis for TP in carrot plant leaves returned a statistically significant low measure in the Sediment treatment. This may suggest that phosphorus absorption was affected by the lower P concentration in the Sediment compared to Farm Soil. Lower P concentration on the Sediment treatment, nevertheless, did not hinder agronomical performance as the parameters measured in the carrot experiment were statistically higher or similar in the Sediment treatment compared to the other two treatments. Higher TOC in the Sediment treatment may have influenced these agronomical results as soil organic matter is known for its positive influence on biological activity, nutrient mineralization, and water-holding capacity (Abiven et al., 2007; Spargo et al., 2011).

Using different evidence, the literature suggests that soil alkalinity limits P availability (Penn & Camberato, 2019) while P content directly affects tomato stem diameter (Chatterjee & Dube, 2004). Conversely, our results show that higher soil pH and limited P concentration did not affect the stem diameter of tomato plants negatively compared to Mixture and Farm Soil treatments. The higher concentration of TOC in the Sediment treatment offers, again, a plausible explanation. The application of organic matter in agricultural soils has been demonstrated to decrease P adsorption by soil colloids and increase P availability (Antelo et al., 2010; Mabagala & Mng'ong'o, 2022).

The initial chemical soil analysis returned optimal nutrient levels for carrot production (Szeląg-Sikora et al., 2019) but sub-optimal for lettuce (Brechner & Both, 2013) and tomato (Sainju et al., 2003). The referred literature indicates that K concentrations on the Sediment treatments pre-planting were below optimal levels for adequate production of lettuce and tomato. Soil alkalinity was sub-optimal for all crops. Previous findings indicate that lettuce reduces its photosynthetic rate under low K availability conditions (Zhang et al., 2017). Production is also known to be affected when pH is alkaline, which also affects K availability (McLean & Watson, 1985). These facts, nevertheless, did not hinder the performance of lettuce plants submitted to the Sediment treatment (i.e., Fresh and dry leaf weights returned statistically significant higher values in the Sediment treatment versus Farm Soil). Putting in perspective, our findings suggest the increased TOC and CEC measures due to sediment application seem to have partially mitigated the limited pre-planting concentrations of Mg, P, and K as the crops grown in the Sediment treatment performed better or similarly in terms of all agronomical parameters compared to Farm Soil.

Other parameters not measured in this project may help explain the reasons for superior crop performance in the Sediment treatment. Physical properties of soils such as aggregation, compaction, and water-holding capacity were not measured, but previous research suggests that Lake Erie sediment has higher water retention compared to commercial substrates (Bhairappanavar et al., 2018). Additionally, research has shown that soil compaction and penetration resistance decrease with increased content of sediments (Guo et al., 2016; Wang et al., 2014). Well-aggregated soils have been found to exhibit better water retention capability and root penetration (Bronick & Lal, 2005; Lal, 1991; Lupwayi et al., 2001; Six et al., 2000). We hypothesize that if these findings were supported by measures conducted in the Sediment relative to Farm Soil and Mixture, it would help explain the superior performance of the agronomical measures in the former treatment.

The concentration of micronutrients and microorganism activity in dredged sediments could also offer additional insights. It has been documented that dredged sediments often contain elevated levels of micronutrients (i.e., Cu, Mn, Mo, Ni, and Zn), which have been shown to improve crop development (Ebbs, 2006). Microorganism diversity and activity were reported to be superior in sediment and biochar substrate blends (Huang et al., 2019). Although our experiment did not evaluate the microbial activity and micronutrient contents, one may argue that these parameters, if observed in significant amounts in Lake Erie dredged sediments, would plausibly benefit crop development. Microbial activity measured in terms of metabolic quotients has been associated with faster organic matter mineralization when soils are amended with biowaste composts (Leifeld et al., 2002).

5 | CONCLUSIONS

This study aimed to assess the impact of three different ratios of dredged sediment from Lake Erie on soil properties and crop development parameters for three specialty crops in a greenhouse setting. According to our expectations, increasing the sediment ratios in the treatments did not negatively affect the growth of lettuce, carrots, and tomatoes. On the contrary, significant improvements were observed in vegetative development, root growth, and fruit production when plants were cultivated using 100% Lake Erie sediment. We attribute these positive outcomes to the improved root conditions provided in the Sediment treatment due to higher TOC, sand content, and CEC. We conjecture that the statistically superior agronomical performance of crops grown in the Sediment may be related to improved biological properties, increased availability of micronutrients, and improved physical parameters not measured in this study.

Based on our findings, we propose several directions for future research: (i) Evaluate the effect of Lake Erie dredged sediments on the physical properties of soils in a comprehensive fashion, including measures on aggregation parameters, penetration resistance and compaction, and water-holding capacity. (ii) Investigate the microbial activity and micronutrient content in Lake Erie sediment to better understand its potential benefits. (iii) Assess the development of specialty crops when grown under different sediment ratios, including blends with other materials such as agricultural lime, mineral fertilizers, manure, and commercial composts that could potentially enhance crop growth and soil properties. (iv) Replicate the experiments in commercial greenhouse and open-field production systems to determine if the positive effects observed in this study hold under varying operational settings. (v) Conduct cost–benefit analyses to determine whether Lake Erie dredge sediment is commercially feasible as a substrate or soil amendment to produce specialty crops. Further exploration in these areas will contribute to a more comprehensive understanding of the benefits and potential applications of Lake Erie sediment in specialty crop production and soil management practices.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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