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Assessing the effects of lake-dredged sediments on soil health: Agricultural and environmental implications for northwestern Ohio

Russell D. Brigham[1] | **Shannon Pelini**[2] | **Zhaohui Xu**[2] | **Angélica Vázquez-Ortega**[1]

[1] School of Earth, Environment and Society, Bowling Green State Univ., 190 Overman Hall, Bowling Green, OH 43403, USA

[2] Dep. of Biological Sciences, Bowling Green State Univ., 217 Life Sciences Building, Bowling Green, OH 43403, USA

Correspondence

Angélica Vázquez-Ortega, School of Earth, Environment and Society, Bowling Green State Univ., 190 Overman Hall, Bowling Green, OH 43403, USA.

Email: avazque@bgsu.edu

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Abstract

Dredging operations produce large amounts of sediments, and when open lake disposal is used, it can pose a threat to water quality. This study examined the potential to use dredged sediment as a farm soil amendment. We conducted greenhouse experiments to determine (a) the physico-chemical health of a farm soil amended with various dredged sediment ratios, (b) nutrient dynamics when the soil blends were subjected to simulated storm events, and (c) the effect of dredged sediment on soybean [*Glycine max* (L.) Merr.] belowground biomass and yield. The soil blends consisted of 100% farm soil, 90% farm soil to 10% dredged sediment, 80% farm soil to 20% dredged sediment, or 100% dredged sediment. After 123 d, the soybean plants were harvested, and physico-chemical analyses were conducted on the soil, soybeans, and percolated stormwater. We found that dredged sediment amendment improved soil health by increasing soil organic matter, cation exchange capacity, and Ca content and by decreasing bulk density and P concentration in a farm soil with P concentration above the agronomic recommended value. Crop biomass and yield averages increased with increasing dredged sediment ratios. Nutrient loss (P and N) in the percolated solutions from the soil blends showed no significant changes when compared to the percolated solutions in the 100% farm soil treatment, indicating no significant contribution to the export of nutrients in percolated water.

1 | INTRODUCTION

Sediment loss primarily from farmland within the Maumee River Watershed is constantly accumulated into the western Lake Erin basin (USACE, 2009). The Toledo Port, Ohio is dredged annually, and nearly 1 million tons of dredged sediments are disposed into the open waters of Lake Erie (OEPA, 2020; USACE, 2009). Open lake-dredged sediment disposal poses a threat to the water quality by resuspending sediment, creating an immediate increase in the total suspended sediment and nutrient concentrations and lowering dissolved oxygen levels (Li et al., 2009; Liu et al., 2019; Moog et al.,

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Abbreviations: CEC, cation exchange capacity; DM0-D0, 100% soil at initial collection; DM0-D123, 100% soil at harvesting, without soybean; DM0-D123S, 100% soil at harvesting, with soybean; DM100-D0, 100% dredged sediment at initial collection; DM100-D123, 100% dredged sediment at harvesting, without soybean; DM100-D123S, 100% dredged sediment at harvesting, with soybean; DM10-D123, 10% dredged sediment at harvesting, without soybean; DM10-D123S, 10% dredged sediment at harvesting, with soybean; DM20-D123, 20% dredged sediment at harvesting, without soybean; DM20-D123S, 20% dredged sediment at harvesting, with soybean; GLDMCI, Great Lakes Dredged Material Center for Innovation; ICP-OES, inductively coupled plasma–optical emission spectrometry; OM, organic matter; SOM, soil organic matter; TN, total nitrogen; TOC, total organic carbon; TP, total phosphorus.

2018). The total amount of N and P released to the water column can be nearly 50 kg (110 lbs.) per load from a hopper dredger having a capacity of 5,000 m^3 (6,540 yd^3) (Liu et al., 2019). An Ohio State Senate Bill, effective as of July 2020, prohibits the open water dumping of dredged material and recommends finding alternative beneficial uses (Gardner & Peterson, 2015).

One potential beneficial use of dredged sediments is to amend farm soils. Dredged sediments can improve soil health by adding organic matter (OM) and nutrients, lowering bulk density, and slightly increasing soil pH (Daniels et al., 2007; Darmody & Ruiz Diaz, 2017; Sigua et al., 2004). Dredged sediments can contain OM in the form of lignin oligomers, marine and terrestrial humic acids, chlorophylls, carbohydrates, and other compounds (Ninnes, et al., 2017; Zhou et al., 2016). Soil OM (SOM) has high surface area, provides C and energy to soil microorganisms, and provides nutrients for plants (Lal, 2006, 2016). Soil organic matter also contains carboxyl, hydroxyl, and phenol functional groups that mediate SOM binding and stabilizing onto clay minerals (Arias et al., 2005). Amending farm soils with dredged sediments that are rich in OM can increase the soil cation exchange capacity (CEC) (Darmody & Ruiz Diaz, 2017) and water retention and decrease bulk density (Develioglu & Pulat, 2017). Recent research has demonstrated improvement in soil health (physical, biological, and chemical) (Huang et al., 2019; Sigua, 2005, 2009) and crop yield in forage grass, corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (Sigua, 2009; Darmody & Ruiz Diaz, 2017).

Numerous studies have primarily focused on the effects of synthetic or organic (e.g., manure, biosolids) fertilizers on agricultural runoff (Dougherty, 2018; Elliott et al., 2005; Hanrahan et al., 2019). To our knowledge, there are no studies investigating nutrient loss from farmland soils amended with lake-dredged sediments in northwestern Ohio. Because dredged sediments can be rich in organic and inorganic C and bioavailable nutrients, its amendment can affect nutrient loss from the farmland, exacerbating eutrophication in the western Lake Erie basin. We hypothesized that OM-rich dredged sediments with optimal CEC and extractable P and Ca content would positively affect soil health indicators and crop yield but may adversely affect the water quality of percolated solutions. In this greenhouse-based scoping study, soil physicochemical properties, soybean aboveground and belowground biomass, and the chemical composition of percolated solutions were investigated. Through this work we aimed (a) to characterize the health (organic and inorganic C, CEC, pH, bulk density, and nutrients) of a soil with elevated P content by amending it with various dredged sediment ratios, (b) to quantify the effect of dredged sediment on soybean belowground biomass and yield, and (c) to determine nutrient dynamics when the soil blends were subjected to induced storm events.

Core Ideas

- Dredged sediment amendment increased soil organic carbon.
- Dredged sediment amendment decreased soil bulk density.
- Average crop biomass and yields increased with increasing dredged sediment ratios.
- Dredged sediment amendment did not increase the nutrient export into waterways.

2 | MATERIALS AND METHODS

2.1 | Study sites and soil collection

The soil used in the greenhouse experiments was collected from a farm in Oregon, OH, and the dredged sediment from the Great Lakes Dredged Material Center for Innovation (GLDMCI) in Toledo, OH. The summers in this region are warm, winters are cold and windy, and it is partly cloudy year-round. Average temperatures and rainfall typically range from −4 to 24 ˚C and from 45 to 92 mm, respectively. The soil series for the farm soil is Latty silty clay (USDA-NRCS, 2020), and the Latty-Toledo-Fulton association makes up to 17% of Lucas County (USDA-NRCS, 2020). The farm soil received Class B biosolids for decades, and the P concentration at the time of collection was 110 mg kg^{-1}. Class B biosolids are treated according to USEPA standards but can contain higher levels of detectable pathogens than Class A biosolids (USEPA, 2000). Biosolid application ceased a decade ago. Farm soil and dredged sediments were gathered from the surface soil layer (30 cm depth) in January 2018. Both soils were air-dried at the greenhouse facility (Agricultural Incubator Foundation). At the time of soil collection, representative subsamples of farm soil (100% soil, DM0-D0) and dredged sediment (100% dredged sediment, DM100-D0) were obtained and placed into 1-gal Ziploc bags. The bags were taken immediately to the laboratory for additional air-drying and pulverization until further analysis. Solid samples were crushed using a Glen Mills Labtechnics Pulverizer with a carbide puck and ring to obtain a fine material of 75 µm. Additional description is included in the Supplemental Material.

2.2 | Greenhouse setup

The air-dried solids were homogenized by (a) piling soil into the middle of a plastic tarp, (b) raking until the pile was spread across the tarp, and (c) reforming the pile back to the center by lifting each corner of the tarp back to the center and repeating six times. Four soil blends were produced by weight, with all soil blends placed in buckets in quadruplicate: DM0, 100% farm soil; DM100, 100% dredged sediment; DM10, 90% farm soil/10% dredged sediment; and DM20, 80% farm soil/20% dredged sediment. The mesocosms were filled by weight with the different soil/dredged sediment ratios leaving 4 cm clear from the top. The buckets did not receive synthetic fertilizer. For 1 mo before planting and throughout the experiment, the mesocosms were watered manually to maintain a soil moisture of 30% to stimulate the microbial community. At planting, six soybean seeds were added to half of the buckets and sowed at a depth of 2.5–4 cm. After germination, seedlings were thinned to one plant per mesocosm. During the soybean growing season from 21 May 2019 to 22 Sept. 2019 (123 d), unintended plants began to grow in the mesocosms, which may have been part of the seed bank from both the farm and the GLDMCI. These plants were immediately removed by hand and left in place. Control buckets were included without soybeans. Indoor greenhouse temperatures were controlled with a heater and a large fan. The minimum inside temperature was set at 21 ˚C, with the average temperature recorded at 31.5 ˚C and average humidity at 43.6% (Supplemental Figure S1). The rainfall events simulated heavy rain events based on the USGS rates of rainfall with average storm rates of 9 mm h^{-1} (USGS, 2019). Five rainfall events were simulated during the growing season. A total of 750 ml was slowly poured over the buckets in a period of 1 h. The free-flowing percolated water after each simulated rainfall event was collected in high-density polyethylene bottles, transported to the laboratory, and stored at 4 ˚C until further analysis. Prior to analysis, the percolated water bottles were weighed, centrifuged to separate solids from the solution, and then filtered using a 0.45-µm nylon syringe filter. More details about the experiment setup are included in the Supplemental Material.

2.3 | Solid phase characterization

Solid phase characterization was conducted twice during the project. The initial characterization (Time 0, one replicate) occurred after gathering the farm soil with elevated P content (DM0-D0) and dredged sediment at the GLDMCI (DM100-D0). The second characterization occurred immediately after soybean harvesting in the greenhouse (123 d). The soybean roots and soybean pods were collected and dried in an oven at 60 ˚C until constant mass was achieved. One soil core sample was collected to a depth of 15 cm, placed in plastic bags, and air-dried under a fume hood. For bulk density analysis, an additional core sample was oven-dried at 105 ˚C until constant weight was achieved. Soil and plant biomass samples were ground as previously described. Total C, total organic C (TOC), and total inorganic C concentrations in the farm soil, dredged sediment, and plant biomass were measured using the Shimadzu TOC-VCSH equipped with a solid sample module (Shimadzu SSM-5000A). Total N (TN) and total P (TP) were analyzed by the alkaline persulfate digestion method followed by colorimetric detection using a Seal AQ2 Discrete Analyzer (Patton & Kryskalla, 2003). Total major cations, Ca, K, and Mg, were measured following lithium metaborate/tetraborate fusion using inductively coupled plasma–optical emission spectrometry (ICP-OES) and inductively coupled plasma–mass spectrometry (Activation Laboratories). Extractable P (Bray-1), K, Mg, Ca, soil pH, and CEC analyses were conducted by A&L Great Lakes Laboratories.

2.4 | Aqueous phase characterization

A subsample of the percolated solution was characterized as follows. The pH and electrical conductivity (EC) were measured within 1 h of collection. Total organic C, total inorganic C, and TN were measured within 1 wk of collection using high-temperature combustion (Shimadzu TOC-L) equipped with a liquid auto sampler (Shimadzu ASI-L). Total P was analyzed using ICP-OES (iCAP 6000 Series ICP Spectrometer, Thermo Electron Corporation). Prior to ICP-OES analysis, each filtered solution required a 10× dilution prepared with 5% nitric acid solution (nitric acid 67–70%, ARISTAR PLUS for trace metal analysis). Nitrate (NO_3^-–N) and phosphate (PO_4^{3-}–P) concentrations were determined using a Seal AQ2 Discrete Analyzer (Seal Analytical, Inc.). Nutrient loads were calculated by multiplying the raw data by the dilution factor and by the total collected solution at each rainfall event.

2.5 | Statistical analysis

Statistical analyses were conducted using R coding (R Code Team, 2019). The corrplot package was used to calculate the Pearson correlation coefficients for all possible pairwise comparisons of response variables (Wei et al., 2017). The effects of soil treatment were modeled after harvesting and separated between mesocosms with soybean and without soybean (Supplemental Figures S2 and S3). The Shapiro–Wilks test checked for normality on the data, and if normality was met, an ANOVA was conducted (Fox et al., 2020). If normality failed, Levene's test was conducted, and, if passed, a Kruskal–Wallis test was conducted. Failure for both Shapiro–Wilks and Levene's tests required logarithmic, inverse, or square root transformations, and data were reanalyzed through the tests (Ogle et al., 2020). Post hoc Tukey tests were conducted after ANOVA tests, and post hoc Dunn's tests were conducted after Kruskal–Wallis tests (Fox et al., 2020; Wickham et al., 2020).

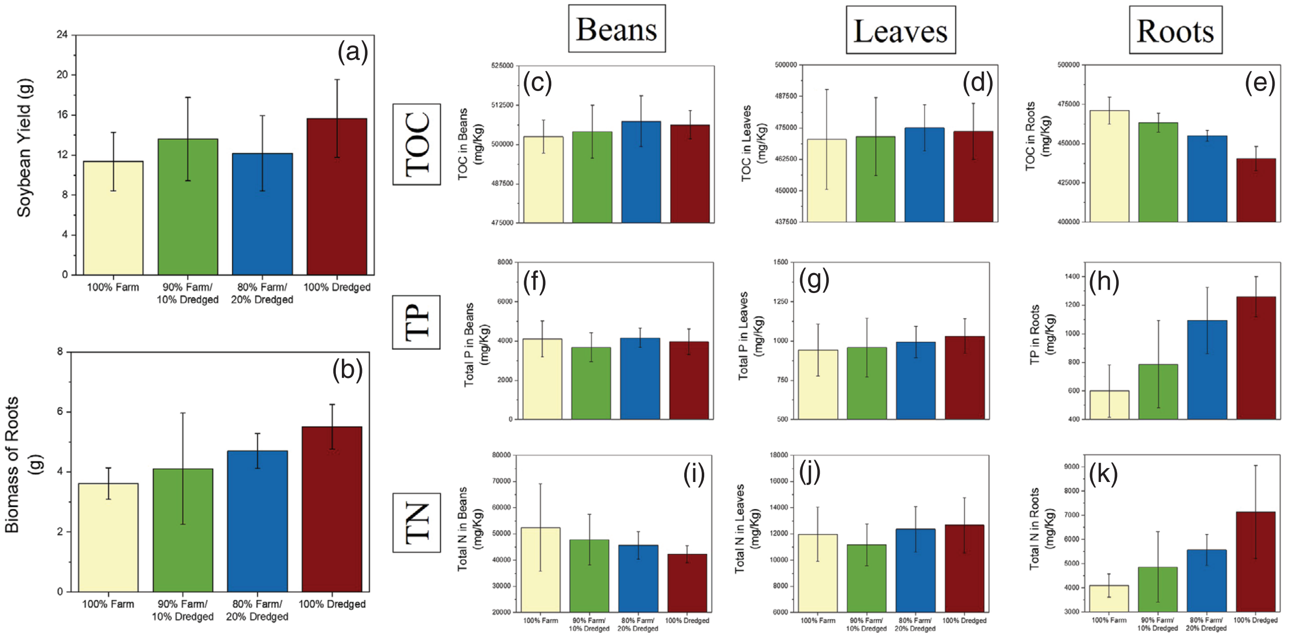

FIGURE 1 (a) Soybean yield; (b) root biomass; and (c–e) total organic C (TOC), (f–h) total P (TP), and (i–k) total N (TN) concentrations in soybean, leaves, and roots as a function of various dredged sediment ratios with and without soybean

3 | RESULTS

The CEC and extractable P and Ca contents in the dredged material are within the recommended optimal values for crops grown in Ohio (Supplemental Table S1; Supplemental Figure S4) (Vitosh et al., 1995). The CEC for DM0-D123 and DM0-D123S (S stands for soybean treatments) did not vary since the time of collection when compared with DM0-D0 (Table 1). However, for DM100-D123 and DM100-D123S, the CEC decreased by an average of 11 and 17%, respectively. The CEC in DM10-D123, DM20-D123, and DM100-D123 were higher when compared to DM0-D123 ($p < .05$) (Table 1; Supplemental Table S2). Similar results were observed for the treatments with soybean ($p < .05$) (Table 1; Supplemental Table S2). The dredged sediment amendments increased extractable Ca in farm soils with soybean by 13 and 28% in DM10-D123S and DM20-D123S when compared to DM0-D0, respectively (Table 1). The addition of dredged sediment to the farm soil induced a decrease in soil extractable P content (Table 1). At 123 d, the average P concentration in DM0-D123S decreased by 12% when compared to DM0-D0. The average values for TOC were higher in soils for both soybean and no soybean as dredged sediment increased (Table 1). The TOC content was higher in the DM100-D123S when compared to DM0-D123S ($p < .05$) (Supplemental Table S2). The DM20-D123 and DM100-D123 treatments had larger TOC than DM0-D123 ($p < .05$) (Supplemental Table S2). The average bulk density lowered with the addition of dredged sediment (Supplemental Figure S5).

Overall, an increasing trend in average values for soybean yield and root biomass was observed (Figure 1a, b). The root system for the DM0-D123S treatment had a more pronounced tap root, thicker lateral roots, and a low density of small and fine roots (Supplemental Figure S6A). However, the DM10-D123S, DM20-D123S, and DM100-D123S treatments contained a higher density of lateral roots and small and fine roots (Supplemental Figure S6B–D).

The chemical characterization of the percolated solution was conducted during five individually simulated storm events throughout the soybean growing season (Figure 2). The 100% dredged sediment with no soybean released the highest TOC loads. Higher TOC loads were released from DM100-D123 when compared to DM10-D123 ($p < .05$) (Supplemental Table S2). The soil treatment with the highest TP loads was the DM0-D123. The TP loads for DM100-D123 were lower when compared to DM0-D123 ($p < .05$) (Supplemental Table S2). Total N loads decreased below 2.5 mg for all soil blends that contained soybean toward the end of the growing season (Figure 2e). The TN in DM100-D123S was higher when compared to DM10-D123S and DM0-D123S ($p < .05$) (Supplemental Table S2); DM100-D123 also had higher TN when compared to DM10-D123 ($p < .05$) (Supplemental Table S2). The percolated solutions for PO_4–P in DM100-D123 compared to DM0-D123, DM10-D123, and DM20-D123 were lower ($p < .05$) (Supplemental Figure 2G; Table S2). There were no differences between any PO_4–P loads for soils containing soybean ($p > .05$) (Supplemental Table S2). The NO_3–N loads showed similar trends as the TN values (Figure 2e), where soils with soybean decreased

TABLE 1 Average chemical characterization values for soil blends at time zero (D0, one replicate) and at harvest (D123, quadruplicates)

Parameters	DM0-D0	DM100-D0	DM0-D123	DM10-D123	DM20-D123	DM100-D123	DM0-D123S	DM10-D123S	DM20-D123S	DM100-D123S
Time	Zero		Final							
Soybean	**No**						**Yes**			
pH	7.5	7.9	7.5 (0.1)	7.8 (0.1)	7.8 (0.1)	7.6 (0.1)	7.6 (0.1)	7.8 (0.1)	7.8 (0.1)	7.8 (0.1)
CEC (meq 100 g^{-1})	21	35	20 (1)	25 (1)	28 (1)	31 (1)	20 (1)	22 (3)	25 (2)	29 (1)
Extractable concentrations										
P (Bray-1)	110	38	109 (3)	92 (4)	91 (4)	67 (1)	97 (4)	85 (6)	78 (6)	67 (1)
Ca	3,150	6,200	2,900 (135)	3,875 (104)	4,550 (147)	5,525 (233)	2,838 (48)	3,550 (394)	4,025 (272)	5,200 (187)
Mg	550	375	584 (30)	548 (32)	551 (38)	348 (9)	579 (24)	490 (61)	469 (44)	346 (9)
K	349	259	275 (13)	273 (15)	279 (22)	232 (11)	244 (14)	216 (26)	210 (14)	187 (8)
Total concentrations										
P	1,120	1,033	479 (75)	466 (12)	557 (85)	458 (8)	462 (14)	459 (5)	564 (25)	445 (14)
N	5,054	5,281	1,163 (135)	1,295 (36)	1,138 (22)	1,210 (71)	1,125 (95)	1,239 (56)	1,173 (64)	1,148 (30)
Ca	10,434	47,598	9,829	10,252	10,734	15,317	10,010	10,372	10,855	15,317
Mg	10,191	15,860	9,648	13,365	16,223	45,168	9,291	11,721	14,365	45,955
K	25,652	22,580	26,482	25,735	25,652	24,157	27,561	27,146	26,897	23,327
Total C	27,601 (373)	42,179 (468)	23,992 (737)	26,852 (1,001)	28,435 (1,701)	41,892 (1,309)	23,919 (450)	27,024 (964)	27,437 (2,990)	42,353 (1,779)
Inorganic C	0	12,739 (2,561)	0	269 (39)	670 (167)	10,098 (1,472)	0	179 (22)	676 (39)	12,145 (926)
Organic C	27,601	29,818	23,992 (737)	26,583 (1,022)	27,765 (1,538)	31,794 (2,108)	23,919 (450)	26,845 (949)	26,761 (3,022)	30,209 (1,387)

Note. Values are in mg kg^{-1} unless otherwise noted. Standard deviations in parentheses with average values of $n = 4$. CEC, cation exchange capacity; SD, buckets with soybean.

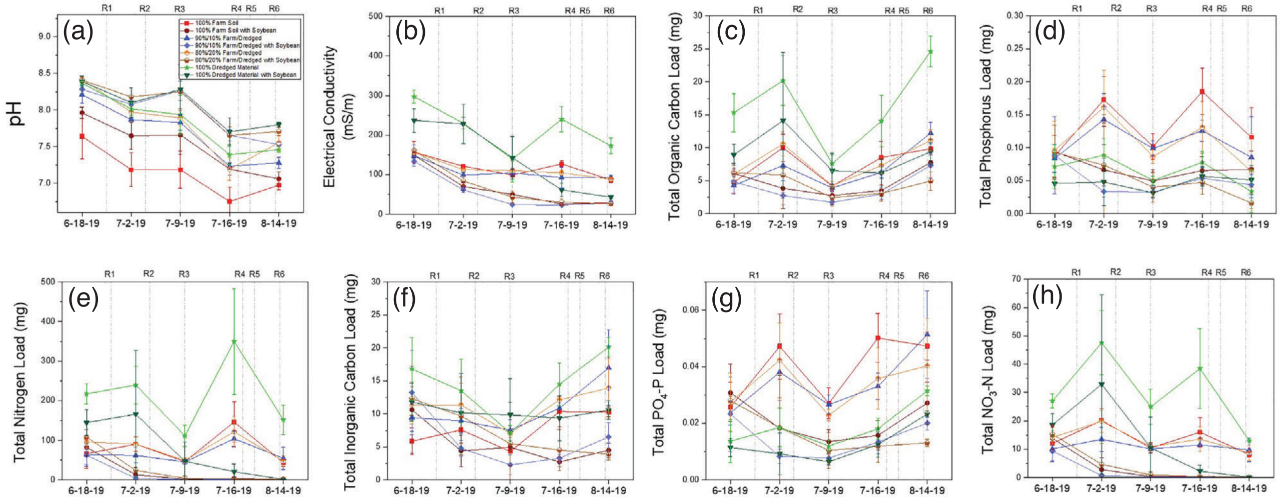

FIGURE 2 (a) pH, (b) electrical conductivity, (c) total organic C, (d) total P, (e) total N, (f) total inorganic C, (g) total PO_4–P, and (h) total NO_3–N loads in percolated solutions as a function of various dredged sediment ratios with and without soybean. R1–R6 represent the stages of soybean growth. At R3, the formation of pods begins to occur

very quickly over time (Figure 2h). All NO_3–N loads for soils with soybean decreased to less than 0.2 mg during the growing season (Figure 2h). There were no differences in NO_3–N loads for any soils with soybean ($p > .05$). The percolated solutions for NO_3–N in DM100-D123 compared with DM10-D123 were higher ($p > .05$) (Supplemental Table S2; Figure 2h).

4 | DISCUSSION

4.1 | Effects of dredged sediment amendment on soil health and nutrient dynamics

We investigated the effects of dredged sediment amendment on soil health, crop biomass and yield, and nutrient loss when applied to a farm soil with elevated P content. The soil physicochemical properties, the soybean aboveground and belowground biomass and yield, and the chemical composition of percolated solutions were investigated using a greenhouse approach. It is well established that high content of soil organic C increases soil fertility, soil stabilization, soil structure, water holding capacity, and crop productivity (Kögel-Knabner & Rumpel, 2018; Newcomb et al., 2017; Oliveira et al., 2017). Studies have shown that average bulk density decreased with increasing dredged sediment ratios, allowing for better root penetration, increased water infiltration, higher porosity, and greater water holding capacity (Wang et al., 2014).

Higher dredged sediment ratios were associated with an increase in TOC in soils with and without soybeans. Other studies using dredged sediment amendments have shown similar increases in SOM and crop yields (Ghaley et al., 2018; Mikanová et al., 2012). An increase of SOM provides soil health benefits such as improving CEC, soil aggregates, and soil resistance to erosion (Miltner et al., 2012; Oliveira et al., 2017). Approximately 25% of SOM is made up of carbohydrates derived from plant polysaccharides, and these organic compounds act as a mucilage (glue) in soils, creating a soil that is more resistant to erosion (Oades, 1984). A comparison between DM0-D0 to DM0-D123 and DM0-D123S showed that average TOC values decreased over the growing season by 13.1 and 13.3%, respectively. However, a comparison between DM100-D123 and DM100-D123S to DM100-D0 showed that average TOC values increased over the growing season by 14.1 and 8.7%, respectively. The results suggest that the presence of dredged sediment not only increased TOC, but also enhanced TOC retention and stabilization. Plausible stabilization mechanisms can include (a) selective preservation due to a high degree of organic matter recalcitrance, (b) spatial inaccessibility of organic matter against decomposer organisms due to occlusion in micro- and macroaggregates and clay intercalation, and (c) organo-metal interactions with Fe-, Al-, Mn-(oxy)hydroxides and aluminosilicates (von Luetzow et al., 2006). However, future research is needed to elucidate the particular C stabilization mechanisms in soils amended with DM.

Higher dredged sediment ratios increased soil CEC values and Ca content in the soil blends (Table 1). Previous studies have shown similar results where CEC increased with the amendment of dredged sediment (Canet et al., 2003; Darmody & Ruiz Diaz, 2017). Lake Erie dredged sediments obtained from the Toledo Harbor are enriched in inorganic carbon and the dissolution of calcite carbonate minerals could potentially contributed to high Ca content in the soil blends, influencing the CEC as well (Dohrmann & Kaufhold, 2009). High CEC positively benefits soil fertility by providing essential nutrients (Ca^{2+}, Mg^{2+}, K^{+}) to plants (Sharma et al., 2015). These essential nutrients promote a diverse and abundant microbial community (Bulluck et al., 2002). Extractable Ca in all treatments will adequately supply Ca to plants (Vitosh et al., 1995). Optimal levels of extractable Mg in farm soils should range from 50 to 1,000 mg kg^{-1} (Vitosh et al., 1995). Extractable Mg in DM0-D0 and DM100-D0 were adequate to support healthy crops (Table 1). Although a decrease occurred in Mg content in soil blends as dredged sediment was added, the Mg content was still acceptable for optimal crop growth (Vitosh et al., 1995).

Class B biosolids were previously applied to the farm soil used in this study as a form of organic fertilizer, providing both N and P nutrients. The biosolid application ended 10 yr ago; however, the extractable P tested at collection time was 110 mg kg^{-1}, which is high according to the Tri-State recommendations (Vitosh et al., 1995). It is not recommended to add P fertilizers to crops if the level of extractable P is greater than 40 mg kg^{-1} (Vitosh et al., 1995). Adding dredged sediment to the farm soil with soybean showed a phosphate decrease in the solid matrix between 23 and 29% for DM10-D123S and DM20-D123S, respectively (Table 1). The decrease in phosphate was attributed primarily to the addition of dredged sediment (dilution effect) and to plant extraction and bioaccumulation. The decrease in extractable P in DM10-D123S and DM20-D123S treatments was not attributed to the loss into percolated solutions because no significant differences were observed in phosphate loads between these treatments and DM0-D123S (Figure 2g). The average bulk density decreased with the addition of dredged sediments to soils with and without soybean. Darmody and Ruiz Diaz (2017) showed similar results, where the soil containing no dredged sediment had the highest bulk density compared with soils treated with dredged sediment. The application of vermicompost, cattle manure, and biosolid in agricultural soils also decreased bulk density (Aksakal et al., 2016; Garcia-Orenes et al., 2005; Guo et al, 2016).

4.2 | Effects of dredged sediment amendment on crop yield and biomass

The amendment of farm soil with dredged sediments did not show any significant changes to soybean biomass or yields; however, the average crop biomass and yields increased with increasing dredged sediment ratios (Figure 1a, b). The visual qualitative comparison of the morphology and abundance of the tap root and lateral roots in the different soil treatments were noticeably different (Supplemental Figure S6). The root system in DM0-D123S showed a thicker tap root, thicker lateral roots, and fewer fine roots than the other soil treatments (Supplemental Figure S6A). The root system in DM10-D123S, DM20-D123S, and DM100-D123S treatments showed a tap root with more branches and greater amounts of finer roots and root hairs than the DM0-D123S (Supplemental Figure S6B–D). Several factors may affect root development, including water availability, CEC, bioavailable nutrients, soil texture, and bulk density (Nawaz et al., 2013; Reintam et al., 2009). The increase in SOM and CEC and decrease in bulk density in treatments containing dredged sediments may have contributed to the observed differences (Darmody & Ruiz Diaz, 2017). Although root organic C concentration significantly decreased with an increase in dredged sediment ratio (Figure 1e), root P content was significantly higher (Figure 1h) and root N on average increased, although not significantly (Figure 1k). In this study, soybean biomass and yield were not significantly higher with the addition of dredged sediment ratios in the greenhouse experiments; the next step will be to conduct field-scale experiments to evaluate these parameters in actual farm conditions.

4.3 | Nutrient loss into percolated water

This study showed that amending farm soil with dredged sediments at various ratios with and without soybean did not significantly affect the leaching of nutrients into percolated waters. Most nutrients were quickly incorporated into the soybean biomass, where rapid decreasing loads were observed in the percolated water over the growing season (Figure 2; Supplemental Figure S7). The TP, TN, PO_4^{3-}–P, and NO_3^{-}–N loads released from DM10-D123S and DM20-D123S showed no significant differences when compared to the loads in DM0-D123S (Figure 2). Similar results were shown for systems without soybean (Figure 2). In contrast, Smith et al. (2007) reported elevated P losses in surface runoff after soil fertilization with inorganic fertilizer, swine manure, and poultry litter. Biosolid amendment has also caused elevated P losses in both surface runoff and percolated water followed by simulated rainfall events (Atalay et al., 2007). However, in-field demonstrations are needed to confirm that dredged sediment amendment will produce lower nutrient loss than the conventional inorganic and organic fertilizers.

4.4 | Implications

In this study, increasing the dredged sediment ratio amendment showed proportional increases in TOC, CEC, and Ca. Conversely, the increase in dredged sediment ratios decreased soil P content in a soil with elevated P content, thereby reducing it toward optimal agronomic values. If farmers are concerned with a lack of extractable Ca and overall soil health, the amendment with dredged sediments seems an adequate choice. Dredged material amendment did not negatively affect soil health or increase P and N leaching in drainage; however, in situ farm experiments are required to examine these processes further. Based on this study, we recommend the application of 10% dredged sediment amendment to minimize the costs associated with transportation and incorporation.

Future research should focus on multi-year, in-field demonstrations using 10% and/or lower dredged sediment ratios and should monitor both soil health and nutrient export. In addition, dredged sediments can be blended with other commonly used organic amendments, such as compost, manure, and biosolids. Furthermore, future research should determine the bioaccumulation and export into waterways of inorganic and organic contaminants (e.g., heavy metals, microcystin, polycyclic aromatic hydrocarbons, polychlorinated biphenyls) as well as microbial and macroinvertebrate dynamics.

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AUTHOR CONTRIBUTIONS

Drs. Vázquez-Ortega and Pelini obtained the grant and planned the greenhouse project. Mr. Brigham set up the greenhouse, collected and analyzed the soil and aqueous samples under the supervision of Drs. Vázquez-Ortega, Pelini, and Xu. Mr. Brigham and Dr. Pelini performed the statistical analyses. All authors contributed intellectually to the written narrative.

CONFLICT OF INTEREST

The authors acknowledge that there are no conflicts of interest.

ORCID

Russell D. Brigham https://orcid.org/0000-0003-4307-8070

Zhaohui Xu https://orcid.org/0000-0002-1866-3254

Angélica Vázquez-Ortega https://orcid.org/0000-0002-4042-8314

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SUPPORTING INFORMATION

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

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