ASSESSING THE EFFECTS OF LAKE DREDGED SEDIMENTS ON SOIL HEALTH: AGRICULTURAL AND ENVIRONMENTAL IMPLICATIONS ON MIDWEST OHIO

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ABSTRACT

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Annually, nearly 1.5 million tons of sediments are dredged from Lake Erie, Ohio. The main method of dredged sediment disposal is open lake disposal. Open lake disposal poses a threat to water quality by re-suspending nitrogen and phosphorus-rich sediments. The Ohio State Senate passed a bill to prohibit the practice of open water disposal after July 2020 and recommends finding alternatives uses of the dredged sediment. One alternative is to use the sediment as an amendment for farm soil. This research aimed to measure the health of soil amended with various dredged sediment ratios, determine nutrient dynamics when the soil blends were subjected to induced storm-events, and quantify the effect of dredged sediment on soybean belowground biomass and yield. We used de-watered dredged sediment from the Great Lakes Dredged Material Center for Innovation and farm soil from a legacy phosphorous (P) farm site in Oregon, Ohio. Soil analysis was conducted on the two soils for baseline data. The soils were thoroughly mixed and separated into four different soil blends; 100% farm soil, 90% farm soil to 10% dredged sediment, 80% farm soil to 20% dredged sediment, and 100% dredged sediment and placed into 32 mesocosms. Soybeans were planted in half of the mesocosms. Daily watering and five random seasonal storm events were conducted during the growing season using synthetic rainwater. After 123 days, the soybean plants were harvested, and soil cores were collected for analysis. Physico-chemical analyses were conducted on the soil, plant biomass, and percolated stormwater. Results showed that dredged sediment amendment improved the quality of the farm soil by providing additional soil organic matter, increasing the cation exchange capacity and decreased P concentration in the legacy P farm soil. Nutrient loss (phosphorous and nitrogen) in the percolated solutions 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 into waterways. Our study showed that adding dredged sediment to farm soil improved the farm soil health and showed no negative environmental impacts with respect to additional nutrient loss.

To my family for encouraging and supporting me through my master’s program.

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INTRODUCTION

Navigating waterways has been an integral part of the history of the United States. In the early 1800s, man-made canals and lake channels helped expand local and national economic development and provided the ability to settle interior portions of the country (Morton & Olson, 2019). However, deposition of sediment from stream bank erosion, agriculture runoff and stormwater events into these waterways required upkeep such as dredging of canals and river channels (USACE, 2009). In 1824, the United States Army Corps of Engineers (USACE) became responsible to clear these waterways and in 1866, funds were specifically dedicated to dredging the Toledo Harbor (Larson, 1981; USACE, 2015). Dredging in Lake Erie is a vital task for the economic development of Ohio port cities. Every year, these cities receive millions of dollars in direct and indirect revenue from shipping goods (USACE, 2009; Carter-Cornell, 2015). The Toledo Harbor (Ohio) alone supported over 33,000 jobs and $4 billion in economic activity in 2017 (TLCPA, 2018). Functional lake channels are necessary to continue this economic activity. Unfortunately, sediment loads from farmland, which makes up the majority of the 4.2 million acre of the Maumee River watershed, as well as, Maumee River stream bank erosion and riverbed sediments accumulate within these channels (USACE, 2009). Nearly 1.5 million tons of dredged sediment are disposed annually into the open waters of Lake Erie (OEPA, 2020). Open lake and river dredged disposal poses a threat to the water quality by re-suspending sediment creating an immediate increase in the total suspended sediment and nutrient concentrations and lower dissolved oxygen levels (Hatin et al., 2007; McQuinn and Nellis, 2007; Li et al., 2009; Moog et al., 2018; Liu et al., 2019). In addition, disturbance of the lake benthos occurs as the sediment cloud impacts the bottom of the lake; thereby, creating a localized burial area (Sweeney et al,, 1975; Vivan et al., 2009). The total amount of nitrogen (N) and phosphorous (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 on July 2020, prohibits the open water dumping of dredged material and recommends to find alternative beneficial uses of the dredged material (Gardner & Peterson, 2015).

One potential beneficial use is to amend farm soils with dredged sediments. Dredged sediments can improve soil health by adding organic matter and nutrients, lowering bulk density, and slightly increasing soil pH (Sigua et al., 2004; Daniels et al., 2007; Darmody and Ruiz Diaz, 2017). Typically, dredged sediment contains OM in the form of lignin oligomers, marine and terrestrial humic acids, chlorophylls, carbohydrates, and other compounds (Zhou et al., 2016; Ninnes, et al., 2017). Soil organic matter (SOM) has high surface area, provides carbon and energy to soil microorganisms and provides nutrients for plants (Lal, 2006, 2016). SOM also contains carboxyl, hydroxyl, and phenol functional groups that mediate SOM binding and stabilizing onto clay minerals (Arias et al., 2005; Lal, 2006, 2016). Amending farm soils with rich-OM dredged sediments can increase the soil cation exchange capacity (CEC) (Darmody and Marlin, 2002; Canet et al., 2003; Darmody and Ruiz Diaz, 2017). The CEC allows for the soil to retain nutrients and prevents the loss of the nutrients out of the soil profile (Wang et al., 2014). Geotechnical tests using dredged sediment showed that water retention increased and bulk density decreased with increasing dredged sediment additions (Develioglu & Pulat, 2017). By improving the soil health, farm soils will be more resilient as soil erosion and compaction will be minimized, and soil infiltration will increase (Magdoff, 2001; Van-Camp et al., 2004; Kibblewhite et al., 2008; Strauss and Albrecht, 2018). Recent research have demonstrated improvement in soil health (physical, biological and chemical) when dredged sediments have been added to farm soils (Canet et al., 2003; Sigua et al., 2004; Sigua, 2005, 2009; Daniels et al., 2007; Koropchak et al., 2016; Benson, 2017; Darmody and Ruiz Diaz, 2017; Mattei et al., 2018; Huang et al., 2019). The addition of dredged sediments are shown to increase yield and plant growth for forage grass, corn and soybean (Sigua, 2005, 2009; Darmody and Ruiz Diaz, 2017). A comparison between a non-amended soil with a soil amended with Potomac River dredged sediment and fertilizer or varying compost rates (0, 25, 50 100 and 150 tons per care) concluded that the amended soils exhibited a decrease in bulk density and an increase in nutrient content (Daniels et al., 2007).

Numerous studies have primarily focused on the effects of synthetic or organic (e.g., manure, biosolids) fertilizers on agricultural runoff (Richards et al., 2001; Shober et al., 2003; Elliott et al., 2005; McCahon Kalcic et al., 2016; Dougherty, 2018; Ward et al., 2018; Hanrahan et al., 2019). To our knowledge, there are no studies investigating the nutrient loss from farmland amended with lake dredged sediments in Midwest Ohio. Since dredged sediments can be rich in organic and inorganic carbon and bioavailable nutrients, its amendment can impact the nutrient loss from the soil profile. In this study, soil physico-chemical properties, soybean above- and belowground biomass, and the chemical composition of percolated solutions were investigated under a greenhouse approach. Through this research we aimed to (1) characterize the health (organic and inorganic carbon, CEC, pH, bulk density, and nutrients) of a legacy P soil amended with various dredged sediment ratios, (2) determine nutrient dynamics when the soil blends were subjected to induced storm-events, and (3) quantify the effect of dredged sediment on soybean belowground biomass and yield.

MATERIALS AND METHODS

Soil Collection

The soil used in the greenhouse experiments was collected from a phosphorous legacy farm in Oregon, Ohio and the dredged sediment from the Great Lakes Dredged Material Center for Innovation (GLDMCI). The farm soil was collected from a conventional farm recently converted to no-till but historically tilled. The farm soil is a Latty silty clay and was last amended with type B biosolids approximately 10 years ago (USDA-NRCS, 2018). The crop rotation for this farm is typical for the area using a corn, soybean alternating method. The crop prior to soil collection was corn. The farm treats the crops with herbicides twice a year. Information related to farm management practices was provided by farmer D. Nelson, via a personal communication. The dredged sediment at the GLDMCI was designed to grow cash crops (e.g., corn and soybean) to demonstrate the effects of dredged material on their yields (Carter-Cornell, 2015). The dredged sediments were allowed to de-water for two years before used in this research. During the de-water period, the dredged sediments were not managed under any agricultural management practices. The dredged sediments were colonized by plants from the seed bank or dispersed by air. Prior to the dredged sediment collection, the vegetation was tilled into the solid matrix.

Farm soil and dredged sediments were gathered from the surface soil layer (~30 cm depth). Both soils were hauled via a dump truck and unloaded in a covered storage area at the Agricultural Incubator Foundation Center to allow for air-drying. The covered storage area included a cement-lined floor which prevented soil mixing or contamination to underlying dirt. Air-drying decreased water content and adhesiveness and allowed for the eventual manual fragmentation and homogenization of the solid material. At the initial time of soil collection, farm soil (100% soil, DM0-D0) and dredged sediment (100% dredged sediment, DM100-D0) samples were taken at locations from the center of mass clumps at random locations through each soil pile. Using a clean shovel and hand trowel, the least disturbed masses were split open and samples were collected. At least 5 representative portions were collected throughout the farm soil and dredged sediment and placed into a one-gallon Ziploc bag. The bags were taken immediately to the lab for either air-drying or freezing until further analysis. Air-drying was conducted using a fume hood for a period of seven days. When necessary, according to the analytical procedure, solid samples were crushed using a Glen Mills Labtechnics Pulverizer. The pulverizer uses a carbide puck and ring to crush the soils to 75 microns.

Greenhouse Setup

This study was conducted using a double completely randomized design (CRD) method for placement of the mesocosms in the greenhouse (Lindsey-Robbins, Vázquez-Ortega, McCluney, & Pelini, 2019). Mesocosms were constructed using 15 liter HDPE square plastic buckets with holes drilled in the bottom of each bucket. A 10 cm diameter funnel was caulked to the bottom to capture percolated water into a 250 ml HDPE bottle. The design in the mesocosms included a 0.64 cm aluminum mesh screen along with a 5 cm layer of river rock to prevent soil loss. The mesocosms were placed on elevated planks for easy access of bottles containing percolated solutions after storm events. The outside rim of each mesocosm was brushed with Tanglefoot sticky trap (Tanglefoot, Marysville, OH) to prevent outside invertebrates from crawling into the mesocosms.

Prior to being placed into mesocosms, the air-dried soil was homogenized by (1) piling soil into the middle of a plastic tarp, (2) raking until the pile was spread across the tarp and (3) 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 consisting of 100% farm soil (DM0), 100% dredged sediment (DM100), 90% farm soil/10% dredged sediment (DM10), and 80% farm soil/20% dredged sediment (DM20) with all soil blends placed in buckets in quadruplicate. The mesocosms were filled up with the different soil-to-dredged sediment ratios leaving 4 cm clear from the top. The mesocosms were placed north-to-south in a greenhouse in two adjacent columns. Before planting, the mesocosms were watered for a month to stimulate the microbial community. At planting, six soybean seeds were added to the designated mesocosms and sowed at a depth of 2.5 cm to 4 cm. After germination, seedlings were thinned to one plant per mesocosm. During the soybean growing season from May 21, 2019 to September 22, 2019 (123 days), 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. Careful removal was conducted to prevent damage to the soybean plants.

Mesocosms were watered daily to maintain a minimum of 30% soil moisture content. Soil moisture percentage was measured using a Delta-T Devices Ltd SM150T Soil Moisture Kit, specifically using a HH150 meter and SM150T soil moisture sensor. Indoor greenhouse temperatures were controlled with a heater and 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%. Synthetic rainwater matched natural North American rain with pH of 5.2 and conductivity of 76 µS/cm. The synthetic rainwater was prepared by using ultrapure water (ELGA Labwater PURELAB® flex, resistivity @ 25 °C is 18.2 MΩ-cm), pH and electrical conductivity (EC) were adjusted using 10% hydrochloric acid (VWR Chemicals Aristar® Plus CAS-7647-01-0 MW/PM 36.46) and sodium chloride (Avantor Sodium Chloride, Granular AR® CAS-7647-14-5 FW 58.440), respectively.

Five storm events were conducted during the soybean growing season. The storm events were conducted at variable time intervals to simulate storm events during any given crop growing season. The storm events simulated very heavy rain events based on the USGS rates of rainfall with average storm rates of 9 mm per hour (USGS, 2019). The typical length of time varied for each heavy rain event based on temperature and soil moisture of the mesocosms.

Analytical Methods

Aqueous Phase Characterization

The percolated water after each storm event was collected in 250 ml high-density polyethylene bottles and transported to the Bowling Green State University Aqueous and Terrestrial Geochemistry Laboratory for analysis. Prior to analysis, the percolated water bottles were weighed, then centrifuged to separate solids from the solution, and then filtered into 125 ml polyethylene bottles. The percolated water was filtered using the syringe filter method, where a 60 ml syringe (Henke Sass Wolf) was filled with solution and pressed through a 0.45 µm nylon syringe filter (PerkinElmer part #02542880). The pH and conductivity were measured within an hour of collection. The total carbon (TC), total inorganic carbon (TIC) and total nitrogen (TN) were measured within a week of collection using high temperature combustion catalytic oxidation followed by a non-dispersive infrared (NDIR) detection of CO_2 (Shimadzu TOC-L) equipped with a liquid auto sampler (Shimadzu ASI-L). Total phosphorous (TP) was analyzed using the Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) (iCAP 6000 Series ICP Spectrometer, Thermo Electron Corporation). Prior to ICP-OES analysis, each filtered solution required a 10x dilution prepared with 5% Nitric Acid solution (Nitric acid 67 - 70%, ARISTAR® PLUS for trace metal analysis, CAS Number: 7697-37-2, VWR Chemicals BDH). The calibration curve was prepared using a single element ICP/MS certified reference standard for phosphorus, (ARISTAR ®, VWR Chemicals BDH). Nitrate (NO^{3-}) and phosphate (PO_4^{3-}) concentrations were tested using a Seal AQ2 Discrete Analyzer (Seal Analytical, Inc, Mequon, WI). Nutrient loads were calculated by multiplying the raw data by the dilution factor and by the total collected solution at each rain event.

Solid Phase Characterization

Solid phase characterization was conducted twice during the project. The initial characterization occurred after gathering the farm soil at the legacy P site (DM0-D0) and dredged sediment at the GLDMCI (DM100-D0). The second characterization occurred in the mesocosms immediately after soybean harvesting (123 days). The soybean roots, remaining leaves, and soybean pods were collected and dried in an oven at 60 °C until constant weight was achieved, and the constant weight was recorded. Soil core samples were collected to a depth of 15 cm and placed in plastic bags then air-dried under a fume hood for further physico-chemical characterization. For bulk density analysis an additional core sample was oven-dried at 105 °C until the weight was constant. All solids except for the leaves were crushed using a Glen Mills Labtechnics Pulverizer to 75 microns. The leaves were crushed using an agate Cole and Parmer mortar and pestle to reduce the loss of matter that typically occurs when using a mill pulverizer. TC, TOC, and TIC concentration in the farm soil, dredged sediment, and plant biomass (roots, leaves and beans) were measured using the Shimadzu TOC-VCSH equipped with a solid sample module (Shimadzu SSM-5000A). Soil and plant certified reference materials (Lecco Company) with carbon concentration of 3.82% and 71.66% were used, respectively. TN and TP were analyzed by the alkaline persulfate digestion method followed by colorimetric detection using a Seal AQ2 Discrete Analyzer (Patton and 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 mass spectrometry (ICP-MS) (Activation Laboratories, Ancaster, Ontario). Bioavailable P (Bray-1), K, Mg, Ca, soil pH and CEC analyses were conducted by A&L Great Lakes Laboratories (Fort Wayne, Indiana).

Statistical Analysis

Statistical analyses were implemented using R coding (R Code Team, 2019). Given the likely correlations among environmental variables (e.g., soil nutrients, soil CEC, soil carbon content, soybean biomass, percolated solution contents), the corrplot package was used to calculate the Pearson correlation coefficients for all possible pairwise comparisons of response variables (Wei et al., 2017). A subset of these environmental variables was selected to use in further analyses. The effects of soil treatment were modeled after harvesting and separated between mesocosms with soybean and for those without. 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 re-analyzed 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).

RESULTS

Soil Physico-chemical Characteristics

Soil average pH values at time zero for both farm soil (DM0-D0) and dredged sediment (DM100-D0) were 7.5 and 7.9, respectively (Table 1). At 123 days, average soil pH values in all dredged sediment treatments, with and without soybeans, ranged from 7.5 to 7.8 (Table 1). Farm soil (100%) at harvest with and without soybeans (DM0-D123S and DM0-D123, respectively) had slightly lower soil average pH values than other soil treatments (Figure 1A). The 90% farm soil/10% dredged sediment (DM10-D123S), 80% farm soil/20% dredged sediment (DM20-D123S) and 100% dredged sediment (DM100-D123S) with soybean measured similar pH values at 7.8 (Figure 1A). No significant differences in pH values occurred in soils with soybean ($p>.05$). However, soils without soybean showed significantly higher pH between 90% farm soil/10% dredged sediment (DM10-D123) and 80% farm soil/20% dredged sediment (DM20-D123) when compared to 100% farm soil (DM0-D123) (df=3, F=11.48, $p=.0013$ and $p=.0026$, respectively). The cation exchange capacity (CEC) values for DM0-D0 and DM100-D0 were 21 and 35 meq $100g^{-1}$, respectively (Table 1). The CEC for DM0-D123 and DM0-D123S remained very similar at the time of collection. However, for DM100-D123 and DM100-D123S the CEC decreased by an average of 4 and 6 meq $100g^{-1}$, respectively. The DM10-D123 and DM20-D123 had a slightly higher CEC than DM10-D123S and DM20-D123S, respectively (Table 1, Figure 1B). DM0-D123 contained the lowest values of CEC at 20 meq $100g^{-1}$ and DM100-D123 had the highest value at 31 meq $100g^{-1}$ (Table 1 and Figure 1B). The CEC in DM10-D123, DM20-D123, and DM100-D123 were significantly higher when compared to DM0-D123 (df=3, F=87.01, $p=.0003$, $p<.0001$, $p<.0001$, respectively; Figure 1B). There was significantly higher CEC when comparing DM20-D123S and DM100-D123S to DM0-D123S (df=3, F=25.66, p=.0048 and p<.0001 respectively).

Bioavailable soil phosphorous (P) concentrations in DM0-D0 and DM100-D0 were 110 and 38 mg kg^{-1}, respectively (Table 1). The addition of dredged sediment to the farm soil induced a decrease in P (Figure 1C, Table 1). At 123 days, the average P concentration in DM0-D123S decreased to 97 mg kg^{-1}. The soil blends with soybean plants (DM10-123S and DM20-123S) showed lower average P concentrations than the blended soils with no soybeans (DM10-D123 and DM20-D123). Bioavailable P displayed significantly lower values as dredged sediment increased for DM10-D123S, DM20-D123S and DM100-D123S compared to DM0-D123S (df=3, F=32.62, p=.0097, p=.0003, and p<.0001 respectively, Figure 1C) and with DM10-D123, DM20-D123 and DM100-D123 compared to DM0-D123 (df=3, F= 95.89, p<.0001 for all three blends, Figure 1C). Bioavailable soil calcium concentrations in DM0-D0 and DM100-D0 were 3,150 and 6,200 mg kg^{-1}, respectively (Table 1). At 123 days, bioavailable average Ca concentrations in all dredged sediment treatments, with and without soybeans, ranged from 2,900 to 5,525 mg kg^{-1} (Table 1, Figure 1D). The dredged sediment amendments increased Ca in farm soils with soybean by 13% and 28% in DM10-D123S and DM20-D123S, respectively (Table 1). Average Ca concentrations in soils without soybean plants were slightly higher than those with soybean plants. Bioavailable Ca in soils at harvest showed significantly higher values as dredged sediment ratios increased when DM10-D123S, DM20-D123S and DM100-D123S were compared to DM0-D123S (df=3, F=59.19, p=.0098, p=.0001, and p<.0001, respectively, Figure 1D) and when DM10-D123, DM20-D123 and DM100-D123 were compared to DM0-D123 (df=3, F=200, p<.0001 for all three blends, Figure 1D).

Bioavailable soil magnesium (Mg) concentrations in DM0-D0 and DM100-D0 were 550 and 375 mg kg^{-1}, respectively (Table 1). At 123 days, bioavailable average Mg concentrations in all dredged sediment treatments, with and without soybeans, ranged from 346 to 584 mg kg^{-1} (Table 1, Figure 1E). Overall, average bioavailable Mg concentrations lowered as the dredged sediment ratio increased. The 100% farm soil with and without soybean showed the highest average bioavailable Mg concentrations. Overall, Mg concentrations were higher in soils without soybean than soils with soybean (Figure 1E). Mg concentrations were significantly lower as dredged sediment ratios increased when comparing DM10-D123S, DM20-D123S and DM100-D123S to DM0-D123S (df=3, F=23.49, p=.035, p=.0093, and p<.0001, respectively, Figure 1E); however, no significant values were shown for soils with no soybean. Bioavailable soil potassium (K) concentrations in DM0-D0 and DM100-D0 were 349 and 259 mg kg^{-1}, respectively (Table 1). At 123 days, bioavailable average K concentrations in all dredged sediment treatments, with and without soybeans, ranged from 187 to 275 mg kg^{-1} (Table 1, Figure 1F). Generally, average bioavailable K concentrations were higher in the treatments without soybean plants. The DM100-D123S treatment had the lowest K concentrations (Table 1, Figure 1F). Bioavailable K concentrations displayed lower values as dredged sediment ratios increased for both soils with soybean and without soybean. However, significantly lower values were shown only when comparing DM100-D123S to DM0-D123S (df=3, F=7.7, p=.0022, Figure 1F) and between DM100-D123 to DM0-D123 (df=3, F=5.17, p=.0333, Figure 1F).

Total inorganic carbon (TIC) was not detected in the farm soil (DM0-D0, DM0-D123 or DM0-D123S) (Table 1). Dredged sediments (DM100-D0) contained 12,361 mg kg^{-1} of TIC. TIC in the soil blends were slightly higher as the dredged sediment ratios increased (Figure 2A, Table 1). At 123 days, there was a significant decreased in TIC content between DM100-D123S to

DM0-D123S (df=3, F=5.34, p<.0001, Figure 2A) and between DM100-D123 to DM0-D123 (df=3, F=15.75, p<.0001, Figure 2A). Total organic carbon (TOC) concentrations in soils at time zero for both farm soil (DM0-D0) and dredged sediment (DM100-D0) were 27,601 and 29,818 mg kg^{-1}, respectively (Table 1). At 123 days, TOC concentrations in all dredged sediment treatments, with and without soybeans, ranged from 23,919 to 31,794 mg kg^{-1} (Table 1). Average TOC concentrations at 123 days for DM20-D123 and DM100-D123 treatments were slightly higher than those with soybean (DM20-D123S and DM100-D123S) (Figure 2B). The average values for TOC were higher in soils for both soybean and no soybean as dredged sediment increased (Figure 2B). The TOC showed significantly higher values between DM100-D123S and DM0-D123S (df=3, F=8.71, p=.0013, Figure 2B) and with DM20-D123 and DM100-D123 when compared to DM0-D123 (df=3, F=15.75, p=.0211 and p=.0002, respectively, Figure 2B).

Total phosphorus (TP) concentrations in soils at time zero for both farm soil (DM0-D0) and dredged sediment (DM100-D0) were 1,120 and 1,033 mg kg-1, respectively (Table 1). At 123 days, TP concentrations in all dredged sediment treatments, with and without soybeans, ranged from 445 to 564 mg kg-1 (Table 1). Total phosphorus (TP) concentrations were similar between each treatment with and without soybean plants (Figure 2C). The TP trend did not follow that of the bioavailable P (Figure 1C). The highest detected amount of TP was observed in both DM20-D123 and DM20-D123S treatments (Table 1, Figure 2C). No significant relationships existed between TP concentrations in soils with no soybean (p>0.05) as a function of dredged treatments. The soils containing soybean showed significant differences in TP when comparing DM20-D123S to DM100-D123S (df=3, F=1.89, p=.0109, Figure 2C). Total nitrogen (TN) concentrations in soils at time zero for both farm soil (DM0-D0) and dredged sediment (DM100-D0) were 5,054 and 5,281 mg kg-1, respectively (Table 1). At 123 days, TN concentrations in all dredged sediment treatments, with and without soybeans, ranged from 1,125 to 1,295 mg kg-1 (Table 1). In general, average total N (TN) concentrations were slightly higher in the treatments with no soybean, except for DM20-D123 (Figure 2D). The 90% farm soil/10% dredged sediment treatment for both soybean and no soybean exhibited the highest TN concentrations (Figure 2D). No statistically significant difference for TN was found between any of the soils containing soybean and without soybean ($p>0.05$). The average bulk density values were higher with soybean plants than without soybean plants (Figure 3). The average bulk density lowered with the addition of dredged sediment; however, no significant differences were shown for soils containing soybean ($p>0.05$). In treatments with no soybean plants, the bulk density was significantly lower when comparing DM100-D123 to DM0-D123 (df=3, F=87.01, p=.0226, Figure 3).

Soybean Biomass and Chemical Characteristics

Overall, the average values for soybean yield and root biomass showed greater mass with an increase in dredged sediment ratios (Figure 4A and Figure 4B, respectively), but were not significantly different for either soybean yield ($p>0.05$) or root biomass ($p>0.05$). The root system contained variability between individual mesocosms; however, notable differences between the root structures was observed (Figure S1). Generally, the root system for the 100% farm soil had a more pronounced tap root, thicker lateral roots and a low density of small and fine roots (Figure S1A). The soil blends (90% farm soil/10% dredged sediment and 80% farm soil/20% dredged sediment) contained a higher density of lateral roots and small and fine roots (Figure S1B and Figure S1C). The 100% dredged sediment roots were similar to the soil blends where the lateral roots were finer and more abundant than the 100% farm soil, but had more abundance of finer roots than the soil blends (Figure S1D). The TOC, TP, and TN content in beans, leaves and roots are shown in Figure 5. The TOC averages in beans were higher with an increase in dredged sediment ratios (Figure 5A). The treatment with the highest average value was the 80% farm soil/20% dredged sediment, but the results were not significant (p>0.05, Figure 5A). Similarly, TOC in leaves were higher as dredged sediment ratios increased; however, this was not significant (p>0.05, Figure 5B). However, the root TOC were significantly lower as dredged sediment ratios increased in farm soil when DM20-D123S and DM100-D123S was compared to DM0-D123S (df=3, F=14.54, p=.0283 and p=.0002, respectively, Figure 5C). The root TOC decreased significantly between DM10-D123S compared to DM100-D123S (df=3, F=14.54, p=.0283 and p=.0025, Figure 5C). The average values for TP in beans did not show any trends between treatments, and there were no significant differences between TP in beans and increased dredged sediment ratios (p>0.05, Figure 5D). The TP averages in leaves were slightly higher as dredged sediment ratios increased; however, there were no significant differences in TP (p>0.05, Figure 5E). Roots showed higher values in TP as the dredged sediment ratio increased when comparing DM20-D123S and DM100-D123S to DM0-D123S (df=3, F=6.73, p=.0441 and p=.0073, respectively, Figure 5F). The TN in beans showed slightly decreasing averages with increasing dredged sediment ratios (Figure 5G). However, there were no significant differences between TN in beans and increased in dredged sediment ratios (p>0.05). The TN was slightly higher in leaves as the dredged sediment ratio increases (Figure 5H). Nevertheless, there were no significant differences between TN in leaves and dredged sediment ratios (p>0.05). The TN were significantly higher in roots when comparing DM100-D123S to DM0-D123S (df=3, F=0.37, p=.028, Figure 5I).

Nutrient Loads in Percolated Solutions

The chemical characterization of the percolated solution was conducted during five individually simulated storm events throughout the soybean growing season. Prior to statistical analysis, the variability of the percolated solutions required all parameters (TOC, TIC, TP, PO_4, TN, NO_3, K, Mg, Ca, EC, and pH) be averaged for all rainfall events. During the growing season, the pH for percolated solutions became more acidic over time for all soil blends regardless of the presence of soybean plants (Figure 6A). Overall, the pH values in percolated solutions were more basic in soils containing soybeans, regardless of dredged sediment treatment (Figure 6A). The average pH in the percolated solutions that contained soybean was significantly higher when comparing DM100-D123S to DM0-D123S (df=3, F=0.13, p=.011, Figure 6A). Significantly lower values were shown when comparing DM10-D123S and DM20-D123S to DM100-D123S (df=3, F=0.13, p=.0021 and p=.017, respectively, Figure 6A). The average pH in the percolated solutions with no soybeans were significantly higher when comparing DM10-D123 and DM20-D123 to DM0-D123 (df=3, F=47.08, p=.0013 and p=.0026, respectively, Figure 6A). In general, the electrical conductivity (EC) of the percolated solutions for the soil treatments with and without soybean showed decreasing trends over time (Figure 6B). The EC decreased faster per unit of time for all treatments containing soybean than treatments with no soybean (Figure 6B). In mesocosms without soybeans, the EC values for the soil treatment types did not vary significantly (p>0.05). In percolated solutions containing soybeans, there was significantly higher EC for DM100-D123S compared to DM0-D123S, DM10-D123S and DM20-D123S (Df =3, F=9.95, p=.011, p=.0021 and p=.017, respectively, Figure 6B).

Nutrient loads measured in the percolated solutions for each storm event included TOC, TP, TN, TIC, PO_4 and NO_3 (Figure 7). TOC loads were consistently lower in soil treatments containing soybean plants when compared to soils with no soybean (Figure 7A). The 100% dredged sediment with no soybean released the highest TOC loads. There was a significantly higher TOC load for DM100-D123 when compared to DM10-D123 (Df=3, F=0.428, p=.0099, Figure 7A). No other significant differences were observed for other TOC loads. TP average loads were generally lower in soil containing soybean than treatments without soybean (Figure 7B). The soil treatment with the highest TP loads was the 100% farm soil with no soybean. The TP loads for DM100-D123 were significantly lower when compared to DM0-D123 (Df=3, F=11.6, p=.0067, Figure 7B). No other significant differences were observed between other TP loads. TN loads decreased below 2.5 mg for all soil blends that contained soybean during the growing period (Figure 7C). The TN loads were lower in soils with soybean than with no soybean (Figure 7C). The DM100-D123S was significantly higher between DM10-D123S and DM0-D123S (Df=3, F=6.782, p=.0048 and p=.0293 respectively, Figure 7C). DM100-D123 was significantly higher than DM10-D123 (Df=3, F=0.6565, p=.0127, Figure 7C). TIC loads varied between storm events (Figure 7D). The 100% dredged sediment with no soybean produced the highest TIC loads (Figure 7D). The TIC loads were higher in soils without soybean than with soybean (Figure 7D). The TIC loads displayed significantly higher values as dredged sediment increased for DM10-D123, DM20-D123 and DM100-D123 compared to DM0-D123 (df=3, F=15.75, p=.0276, p=.0131, and p=.0001, respectively, Figure 7D). In addition, TIC loads were significantly higher between DM100-D123 compared to DM10-D123 and DM20-D123 (df=3, F=15.75, p=.0153, and p=.0304, respectively, Figure 7D). There was no significant difference for TIC loads between any soil treatments containing soybean ($p>0.05$). PO_4 in percolated solutions for soils containing soybean had lower loads than the soils without soybean (Figure 7E). The percolated solutions for PO_4 in DM100-D123 compared to DM0-D123, DM10-D123 and DM20-D123 were significantly lower (df=3, F=11.6, p=.0007, p=.0054 and p=.0077, respectively, Figure 7E). There was no significant differences between any PO_4 loads for soils containing soybean (p>0.05). NO_3 loads showed similar trends as TN values (Figure 7C), where soils with soybean decreased very quickly over time (Figure 7F). All NO_3 loads for soils with soybean decreased to less than 0.2 mg during the growing season (Figure 7F). The NO_3 loads were lower in soils with soybean than soils without soybean (Figure 7F). There were no significant differences in NO_3 loads for any soils with soybean (p>0.05). The percolated solutions for NO_3 in DM100-D123 compared to DM10-D123 were significantly higher (df=3, F=0.956, p=.0099, Figure 7F).

Potassium loads decreased over time to less than 1.2 mg for soils containing soybeans and soils with no soybean show slight decreases (Figure S2A). The DM100-D123S produced the highest K loads (Figure S2A). DM100-D123S had significantly higher K loads than DM0-D123S and DM10-D123S (df=3, F=10.43, p=.003 and p=.0014, respectively, Figure S2A). There were also significant differences for K loads in soils with no soybean, where DM100-D123 had significantly higher K loads than DM0-D123 (df=3, F=0.76, p=.0259, Figure S2A). Magnesium loads in soils with soybean decreased over time to less than 2 mg, while soil with no plants showed slight decreases (Figure S2B). Mg loads were lower in soils with soybean than soils without soybean (Figure S2B). DM100-D123S produced the highest Mg loads (Figure S2B). DM100-D123S had significantly higher Mg loads than DM10-D123S (df=3, F=4.593, p=.0468, Figure S2B). There were also significant differences for Mg loads in soils with no soybean where DM100-D123 had significantly higher Mg loads than DM10-D123 (df=3, F=0.2209, p=.0099, Figure S2B). Calcium loads showed similar trends to K and Mg where soils with soybean loads decrease exponentially (Figure S2C). Ca loads for all soils with soybean decreased to less than 12.5 mg over the growing season, while soils with no soybean show slight decreases (Figure S2C). DM100-D123 had the highest Ca loads among all soil treatments (Figure S2C). DM100-D123S had significantly higher Ca loads than DM10-D123S (df=3, F=5.605, p=.0091, Figure S2C). There were also significant differences for Ca loads in soils with no soybean where DM100-D123 had significantly higher K loads than DM10-D123 (df=3, F=0.0873, p=.0127, Figure S2C).

DISCUSSION

The amendment of dredged sediments to a farm soil (legacy P farm) positively benefited soil health and soybean crops, with no significant nutrient loss into percolated waters. Overall, the increase of dredged sediment ratios in the farm soil ensued significantly higher values for: TOC in soils containing soybeans and without soybean ($p=.0024$ and $p<.001$, respectively, Table 1 and Figure 2B), CEC in the soil blends containing soybeans and without soybeans ($p<.001$ for both, Table 1 and Figure 1B), Ca in soils containing soybeans and without soybeans ($p<.001$ for both, Table 1 and Figure 1D), and Mg in soils containing soybeans ($p<.001$, Table 1 and Figure 1E). The increase in dredged sediment amendment lowered the values for bioavailable P in soils containing soybeans and without soybean ($p<.001$ for both, Table 1 and Figure 1C) and bulk density in soils with no soybean plants ($p=.0333$, Table 1 and Figure 3). Additionally, increased dredged sediment ratios significantly lower OC content in the roots OC ($p<.001$, Figure 5C), but significantly increased P content in the roots ($p=.0065$, Figure 5F). Percolated solutions showed significantly higher loads when dredged sediment ratios increased only for TIC ($p<.001$, Figure 7D).

Effects of Dredged Sediment Amendment on Soil Health and Nutrient Dynamics

TOC content at time zero showed that DM100-D0 was 8% higher than DM0-D0 (29,818 mg kg^{-1} compared to 27,601 mg kg^{-1}, Table 1). At time final, the TOC in soil increased as dredged sediment increased, and significant values were shown when comparing soils containing soybean DM100-D123S to DM0-D123S, and in soils with no soybean, DM100-D123 and DM20-D123 compared to DM0-D123. Other studies using dredged sediment amendments showed similar increases in SOM and also increases in crop yields (Mikanová et al., 2012; Ghaley et al., 2018). An increase of SOM provides soil health benefits such as improving soil fertility, soil structure, crop productivity and soil resistance to erosion (R. Lal, 2006; Miltner et al., 2012; Oliveira et al., 2017). In addition, a 1 g increase in SOM will increase soil moisture content by 1 to 10 g (R. Lal, 2006). Approximately 25% of SOM are made up of carbohydrates derived from plant polysaccharides and these organic compounds act as a glue (mucilage) in soils creating a soil more resistant to erosion (Oades, 1984). The mucilages (viscous substances) are produced by both plant roots and microbes (Oades, 1984). Interestingly, a comparison between 100% farm soil at time zero (DM0-D0) to 100% farm soil at harvest without and with soybean (DM0-D123 and DM0-D123S) showed TOC average values decreased over the growing season by 13.1% and 13.3%, respectively. However, a TOC comparison of 100% dredged sediment at time zero (DM100-D0) to 100% dredged sediment without and with soybean at harvest (DM100-D123 and DM100-D123S) showed an average increased in TOC of 14.1% and 8.7% respectively. The increase in TOC in 100% dredged sediment treatments containing soybean may be due to the soybean roots system's ability to exudate below ground organic compounds (Novelli, Caviglia, & Piñeiro, 2017).

Results from this study demonstrated that amending a farm soil with increasing dredged sediment ratios significantly increased soil CEC values and Ca content. The CEC values at time zero were much higher for dredged sediment than farm soil (35 and 21 meq $100g^{-1}$, respectively, Figure 1B, Table 1). The CEC at time final for both DM10-D123 and DM20-D123 had a higher CEC than DM0-D123. Similar results occurred when comparing DM20-D123S and DM100-D123S to DM0-D123S. 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 (Cornell University, 2007; Sharma et al., 2015). These essential nutrients promote a diverse and abundant microbial community (Bulluck et al., 2002). Bioavailable calcium at time zero in 100% farm soil (DM0-D0) was 3,150 ppm and for 100% dredged sediment (DM100-D0) was 6,200 mg kg^{-1} (Table 1); optimal crop values range from 200 to 8000 Ca mg kg^{-1} (Vitosh, Johnson, & Mengel, 1995). This indicates that, initially, both farm soil and dredged sediments will adequately supply Ca to plants (Vitosh et al., 1995). At 123 days, the dredged sediment amendments increased Ca in farm soils with soybean (Table 1). The increase in exchangeable Ca; however, was not reflected by an increase in soil pH, where the average pH increased only by 4% for both DM10-D123S and DM20-D123S (Table 1). Since Ca is a major and dominant base cation in the dredged sediments and has the ability to replace H+; thereby, potentially making the farm soil more basic, but this was not observed in our soil blends (Mengel, 2008; Culman et al., 2019).

Optimal levels of bioavailable Mg in farm soils should range from 50 ppm to 1000 ppm (Vitosh et al., 1995). Time zero soil analysis showed bioavailable Mg at 550 ppm for farm soil (DM0-D0) and 375 ppm for dredged sediment (DM100-D0), indicating that Mg content was adequate in both soils (Table 1). At 123 days, the Mg content in DM10-D123S and DM20-D123S was reduced by 11% and 15% when compared to DM10-D123 and DM20-D123, respectively (Table 1, Figure 1E). Although a decrease occurred in Mg content in soil blends as dredged sediment was added, the Mg content was still adequate for optimal crop growth (Vitosh et al., 1995).

Class B biosolids were applied to the farm soil used in this study. Class B biosolids are treated according to EPA standards, but can contain higher levels of detectable pathogens than Class A biosolids (U.S. EPA, 2000). The application ended 10 years ago; however, the bioavailable P (Bray-1) tested at collection time was 110 ppm, 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 bioavailable P is greater than 40 to 50 ppm (depending on crop type) (Vitosh et al., 1995). Adding dredged sediment to the legacy P farm soil with soybean showed a significant phosphate decrease in the solid matrix between 23% and 29% for DM10D123S and DM20D123S, respectively (Table 1). The decrease in phosphate is attributed primarily to the addition of dredged sediment (dilution effect) and to plant extraction and bioaccumulation. The decrease in bioavailable P in DM10D123S and DM20D123S treatments was not be attributed to the loss into percolated solutions, since no significant difference was observed in phosphate loads between these treatments and DM0D123S (Figure 7E).

The average bulk density decreased with the addition of dredged sediment to both soils with and without soybean. However, there were no significant differences in bulk densities in all treatments containing soybean. The soils with no soybean had a significant decrease when comparing 100% dredged sediment to 100% farm soil (Figure 3). Darmody and Ruiz Diaz (2017) showed similar results where the soil containing no dredged sediment had the highest bulk density compared to soils treated with dredged sediment. The lack of strong significant differences in bulk density as a function of increasing dredged sediment ratios could be attributed to the solid matrix preparation (e.g., drying, sorting and placement into buckets).

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 averages crop biomass and yields increased with increasing dredged sediment ratios (Figures 4A and 4B). Root systems in different soil treatments were noticeably different (Figure S1, Supplemental Information). Root development in 100% farm soil (DM0-D123S) showed a thicker tap root, thicker lateral roots and fewer fine roots than the other soil treatments (Figure S1A). Roots in treatments including dredged sediments (DM10-D123S, DM20-D123S, DM100-D123S), showed a tap root with more branches and greater amounts of finer roots and root hairs than the 100% farm soil treatment (DM0-D123S) (Figures S1B, S1C and S1D). Several factors may affect root development including water availability, CEC, bioavailable nutrients, soil texture and bulk density (Reintam et al., 2009; Nawaz et al., 2013). The increase in SOM and CEC and decrease in bulk density in treatments containing dredged sediments may be controlling the root development (Cornell University, 2007; Sharma et al., 2015; Lal, 2016; Williams et al., 2016; Darmody and Ruiz Diaz, 2017). Although root OC significantly decreased with an increase in dredged sediment ratio (Figure 5C), root P content was significantly higher (Figure 5F) and root N on average increased although not significantly (Figure 5I). Even though, the soybean biomass and yield were not significantly higher with the addition of dredged sediment ratios in the greenhouse experiments, a field-scale experiment may produce significant values in these parameters.

Nutrient Loss into Waterways

This study showed that amending farm soil with dredged sediments at various ratios with soybean and without did not significantly affect the export of nutrients (TOC, TP, PO_4, TN, NO_3, K, Mg and Ca) into waterways. The bioavailable nutrients were quickly incorporated into the soybean biomass, especially for N, NO_3, K, Mg and Ca, where rapid decreasing loads occurred over the growing season (Table 1, Figure 7C, Figure 7F, Figure S1A, Figure S1B and Figure S1C, respectively). TIC loads were only significantly higher in DM10-D123 and DM20-D123 with respect to DM0-D123 (Figure 7D). In addition, high IC content in percolated solutions might induce high aqueous pH values; however, pH values did not increase indicating that amending soils with dredged sediments had no significant effects on the percolated solution pH (Figure 6A).

Previous studies using various types of inorganic and organic amendments aimed to increased crop biomass and improved soil health; however, there can be unintended negative impacts on water quality (Richards et al., 2001; Shober et al., 2003; Elliott et al., 2005; McCahon Kalcic et al., 2016; Dougherty, 2018; Ward et al., 2018; Hanrahan et al., 2019). However, the use of dredged sediment in this study, showed improvements to soil health and increased soybean biomass, but had no significant impact to water quality. TP and TN loads released from soil blends with soybean (DM10-D123S and DM20-D123S) showed no significant differences when compared to the loads in 100% farm soil with soybean, DM0-D123S (Figure 7B and Figure 7C, respectively). Similar results were shown for TP and TN with no soybean compared to 100% farm soil with no soybean (DM10-D123 and DM20-D123 compared to DM0-D123, Figure 7B and Figure 7C respectively). This was also true when comparing PO_4 and NO_3 loads in DM10-D123S and DM20-D123S compared to DM0-D123S and for soils with no soybean, DM10-D123 and DM20-D123 compared to DM0-D123 (Figure 7E and Figure 7F respectively). Interestingly, when relating the TP and PO_4 loads from DM0-D123S to DM10-D123S a decrease of 29% and 50% was observed, respectively. In addition, TN and NO_3 for DM0-D123S compared to DM10-D123S a decrease by 32% and 40% was observed, respectively. This suggests that using a 10% ratio of dredged sediments in farm soil may decrease TP, TN, PO_4 and NO_3 loads in percolated water. However, in-field demonstrations are needed to confirm these results.

AGRICULTURAL AND ENVIRONMENTAL IMPLICATIONS

Agricultural Benefits

Increasing the dredged sediment ratio showed proportional increases in total organic carbon, cation exchange capacity, and calcium. Conversely, the increase in dredged sediment ratios decreased phosphorous and magnesium content in the blended soils. The legacy P farm soil contained high bioavailable P at the beginning of the study; therefore, reducing the P legacy content in the soils towards optimal agronomic values is beneficial for both the crop system and waterways. Although magnesium decreased with increasing dredged sediment ratio, Mg levels in dredged sediment were optimal for soybean crops.

High content of total organic carbon increases soil fertility, soil stabilization, soil structure, water holding capacity and crop productivity (Oades, 1984; Lal, 2006, 2016; Miltner et al., 2012; Paul, 2016; Darmody and Ruiz Diaz, 2017; Newcomb et al., 2017; Oliveira et al., 2017; Kögel-Knabner and Rumpel, 2018). The increase in CEC allows plants to uptake nutrient more readily (Cornell University, 2007; Dohrmann & Kaufhold, 2009; Sharma et al., 2015). Average bulk density decreased with increasing dredged sediment ratios, allowing for better root penetration, increased water infiltration, higher porosity and greater water holding capacity (NRCS, 2008; Wang et al., 2014; Xu et al., 2016; Darmody and Ruiz Diaz, 2017).

An important aspect of this project was to use various amounts of dredged sediment into the farm soil and measure the response of the soil and soybean to these various ratios. Both ratios (10% and 20% dredged sediment) improved the farm soil health and soybean root system. Aside from Ca and CEC in soils, no other value showed significant differences between the use of 10% dredged sediment and 20% dredged sediment with the 20% ratio exhibiting higher values. If farmers are concerned with lack of Ca in their farm soils, then 20% dredged sediment amendment seems a good choice. However, if the farmers are concerned with the overall improvements to soil health and a more robust crop root system, then 10% dredged sediment amendment would be adequate. When incorporating dredged sediments into farm soils, the logistics related to the cost of transportation and incorporation are important to be considered. Based on the results presented in this study, we recommend the application of 10% dredged sediment amendment to minimize the costs associated with transportation and incorporation. This results need to be confirmed in an in-field demonstration.

Environmental Benefits

Adding dredged sediment to farm soil not only improved the soil health, but also showed that adding up to 10% dredged sediment reduced average nutrient (P and N) loss into waterways. Dissolved inorganic carbon increased in the percolated solutions with an increase in dredged sediment ratios. Dissolved IC should have increased the pH in the percolated solutions; however, a small increase in pH was observed. Previous studies have focused on the use of synthetic (e.g., urea, monoammonium phosphate) and organic (e.g., manure, biosolids) fertilizers to improve crop growth but cause detrimental effects to the water quality of freshwater systems (Richards et al., 2001; Shober et al., 2003; Elliott et al., 2005; McCahon Kalcic et al., 2016; Dougherty, 2018; Ward et al., 2018; Hanrahan et al., 2019). This study showed that dredged sediment amendments enhanced farm soil health while nutrient loss into waterways did not significantly increased when compared to 100% farm soil treatments.

Given the conclusion drawn from this research, the need for future research is identified for several methods. The first is to conduct a greenhouse study to compare dredged sediment added to farm soil at smaller percentages to determine the best application rate of the dredged sediment. Secondly, compare the dredged sediment amendment to other amendments such as biosolids and fertilizer (both synthetic and organic) and blends of each and collect percolated water to test nutrient runoff. Thirdly, conduct a multi-year field test to determine if multi-year amendments of dredged sediments improve soil health over time. This study characterized the nutrient content on soil blends, plant biomass, and percolated water, as well as crop biomass and yield. However, other parameters were not discussed such as bioaccumulation and export into waterways of inorganic and organic contaminants (e.g., heavy metals and microcystin), microbial and macroinvertebrate dynamics. The incorporation of these analyses in future studies will provide a more in-depth and comprehensive picture of the use of dredged sediments as farm amendments to better informed farmers, environmentalists and other stakeholders.

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APPENDIX A: TABLE

Table 1. Average chemical characterization values for soil blends at time zero (D0) and at harvest (D123). Standard deviations in parenthesis with average values of n=4. Some measurements used only one replicate. Values are in mg kg^{-1} unless otherwise noted.

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/100g)	21	35	20 (1)	25 (1)	28 (1)	31 (1)	20 (1)	22 (3)	25 (2)	29 (1)
Bioavailable Concentrations										
Phosphorous (Bray-1)	110	38	109 (3)	92 (4)	91 (4)	67 (1)	97 (4)	85 (6)	78 (6)	67 (1)
Calcium	3150	6200	2900 (135)	3875 (104)	4550 (147)	5525 (233)	2838 (48)	3550 (394)	4025 (272)	5200 (187)
Magnesium	550	375	584 (30)	548 (32)	551 (38)	348 (9)	579 (24)	490 (61)	469 (44)	346 (9)
Potassium	349	259	275 (13)	273 (15)	279 (22)	232 (11)	244 (14)	216 (26)	210 (14)	187 (8)
Total Concentrations										
Phosphorus	1120	1033	479 (75)	466 (12)	557 (85)	458 (8)	462 (14)	459 (5)	564 (25)	445 (14)
Nitrogen	5054	5281	1163 (135)	1295 (36)	1138 (22)	1210 (71)	1125 (95)	1239 (56)	1173 (64)	1148 (30)
Calcium	10434	47598	9829	10252	10734	15317	10010	10372	10855	15317
Magnesium	10191	15860	9648	13365	16223	45168	9291	11721	14365	45955
Potassium	25652	22580	26482	25735	25652	24157	27561	27146	26897	23327

Total Carbon	27601 (373)	42179 (468)	23992 (737)	26852 (1001)	28435 (1701)	41892 (1309)	23919 (450)	27024 (964)	27437 (2990)	42353 (1779)
Inorganic Carbon	0	12739 (2561)	0	269 (39)	670 (167)	10098 (1472)	0	179 (22)	676 (39)	12145 (926)
Organic Carbon	27601	29818	23992 (737)	26583 (1022)	27765 (1538)	31794 (2108)	23919 (450)	26845 (949)	26761 (3022)	30209 (1387)

APPENDIX B: FIGURES

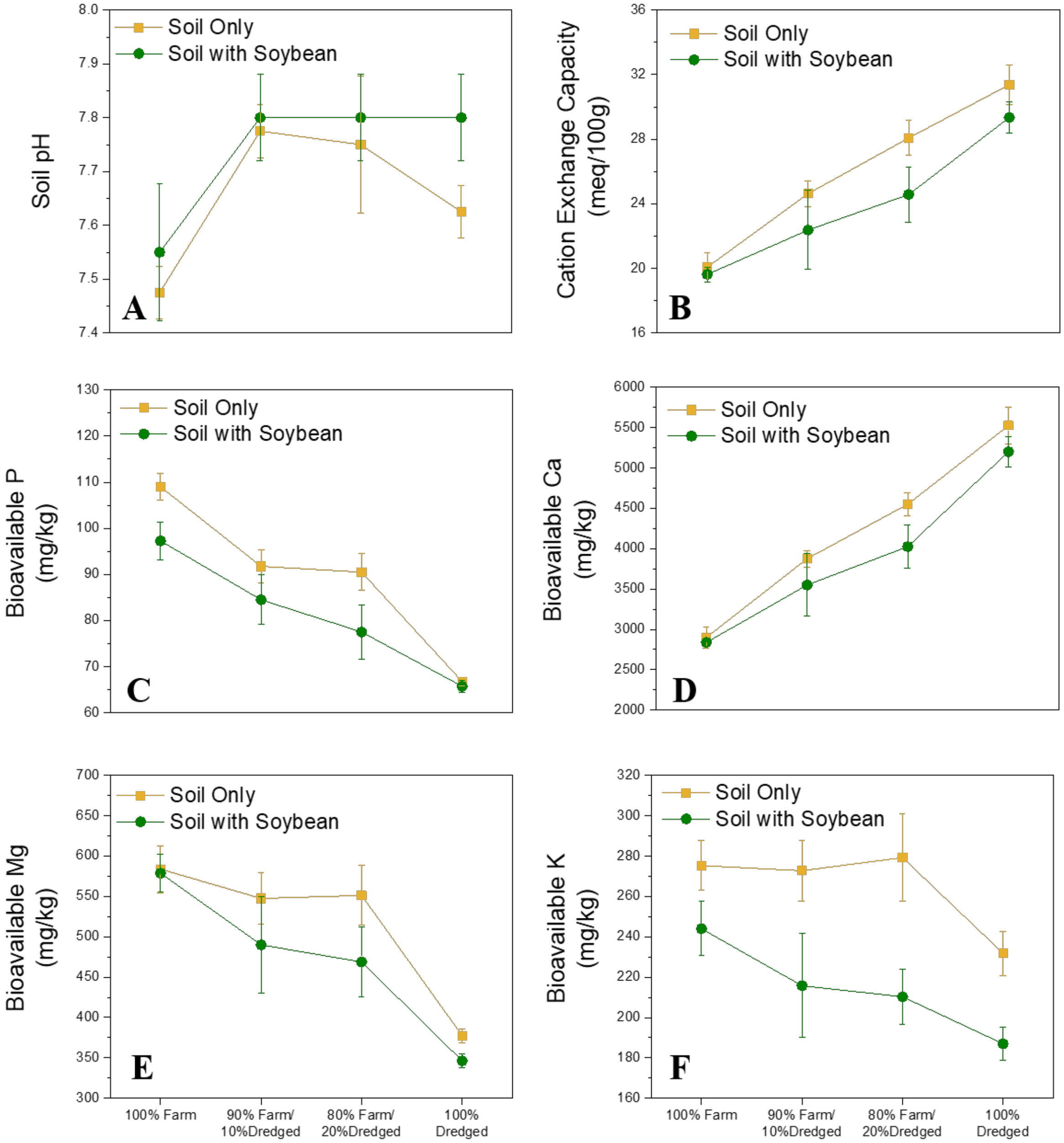


Figure 1. Bulk soil pH (A), CEC (B), and bioavailable P (C), Ca (D), Mg (E), and K (F) concentrations as a function of various dredged sediment ratios with and without soybean.

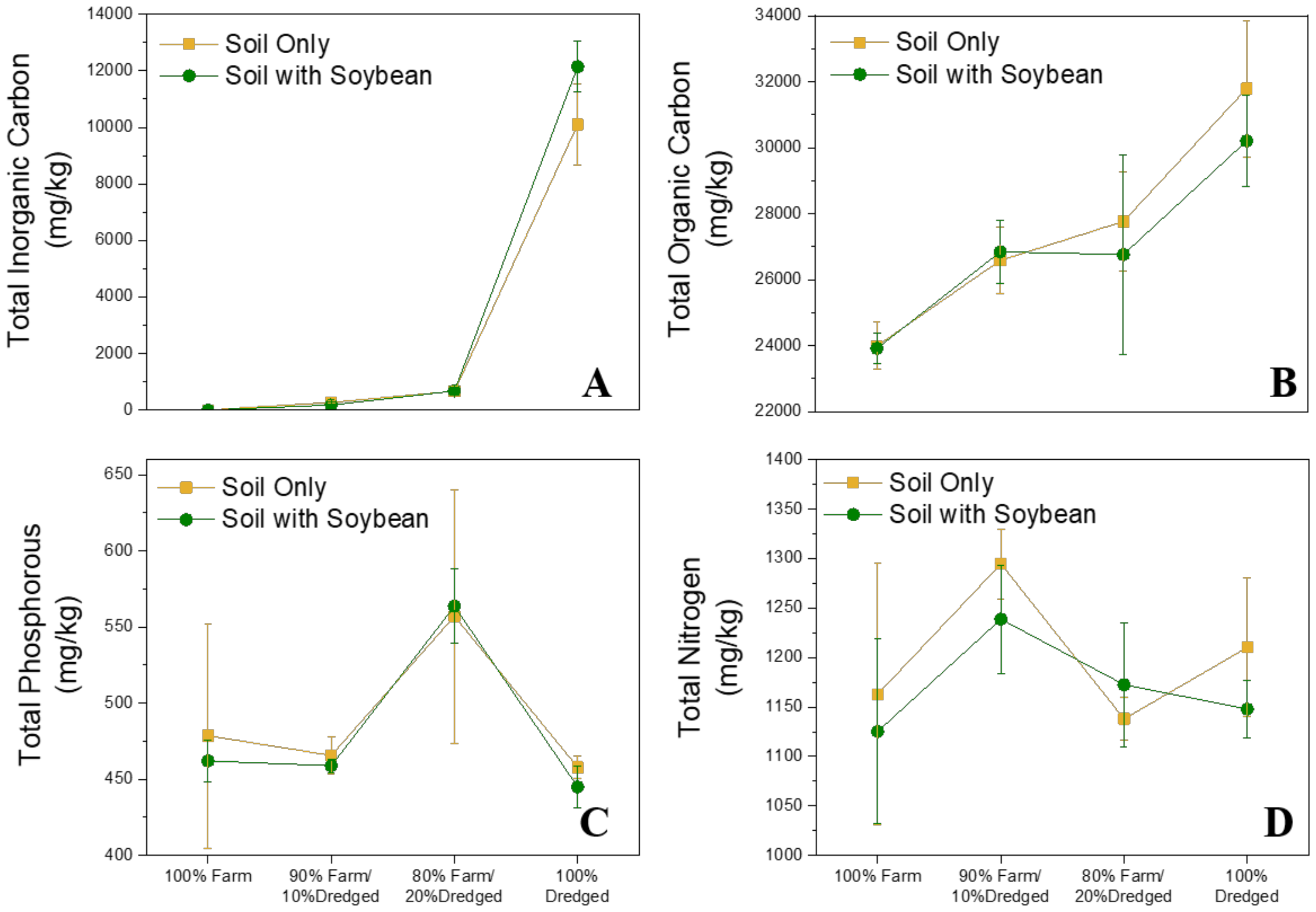


Figure 2. Bulk soil total organic carbon (A), total inorganic carbon (B), total phosphorous (C), and total nitrogen (D) concentrations as a function of various dredged sediment ratios with and without soybean.

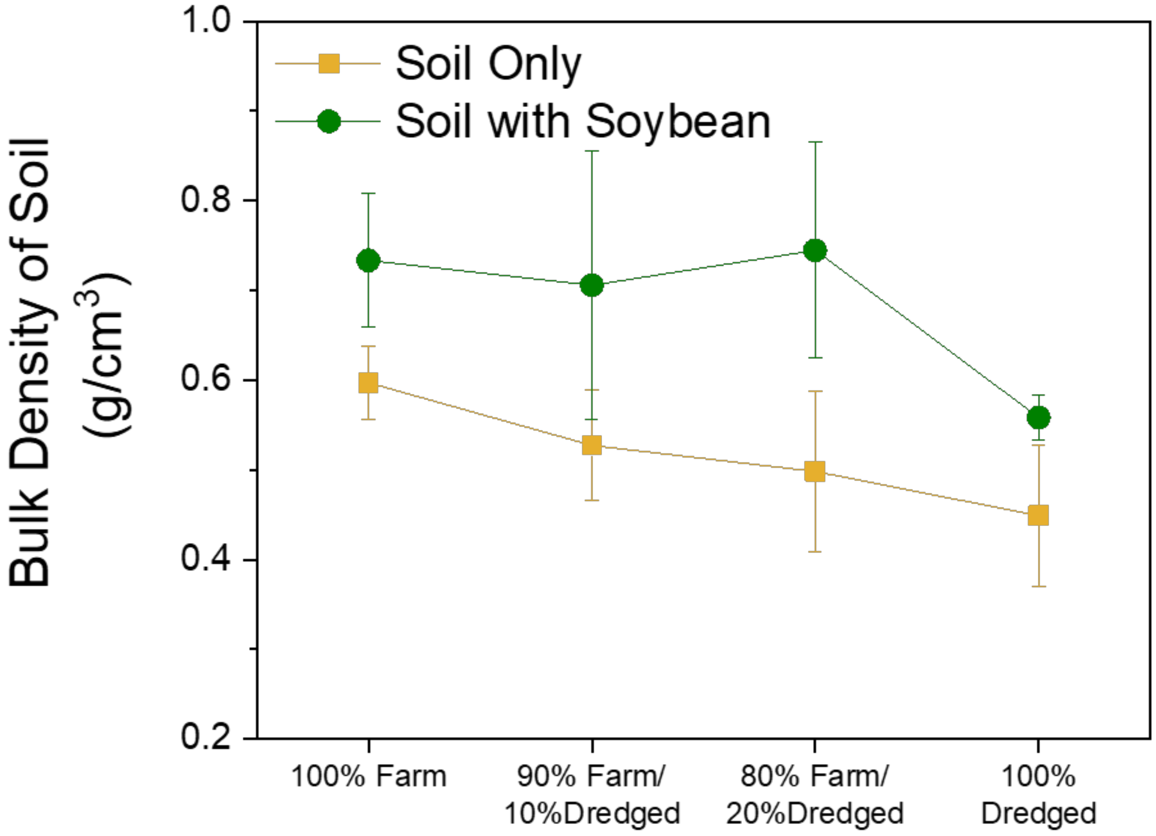


Figure 3. Soil bulk density as a function of various dredged sediment ratios with and without soybean.

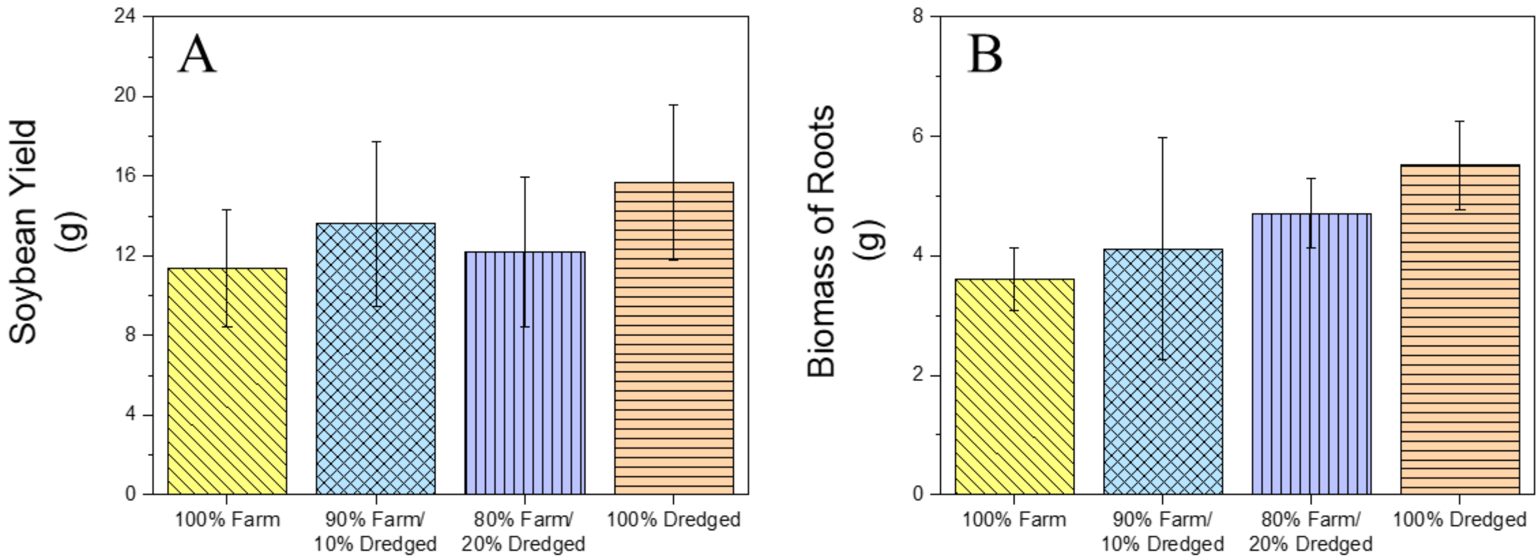


Figure 4. Soybean yield (A) and root biomass (B) as a function of various dredged sediment ratios with and without soybean.

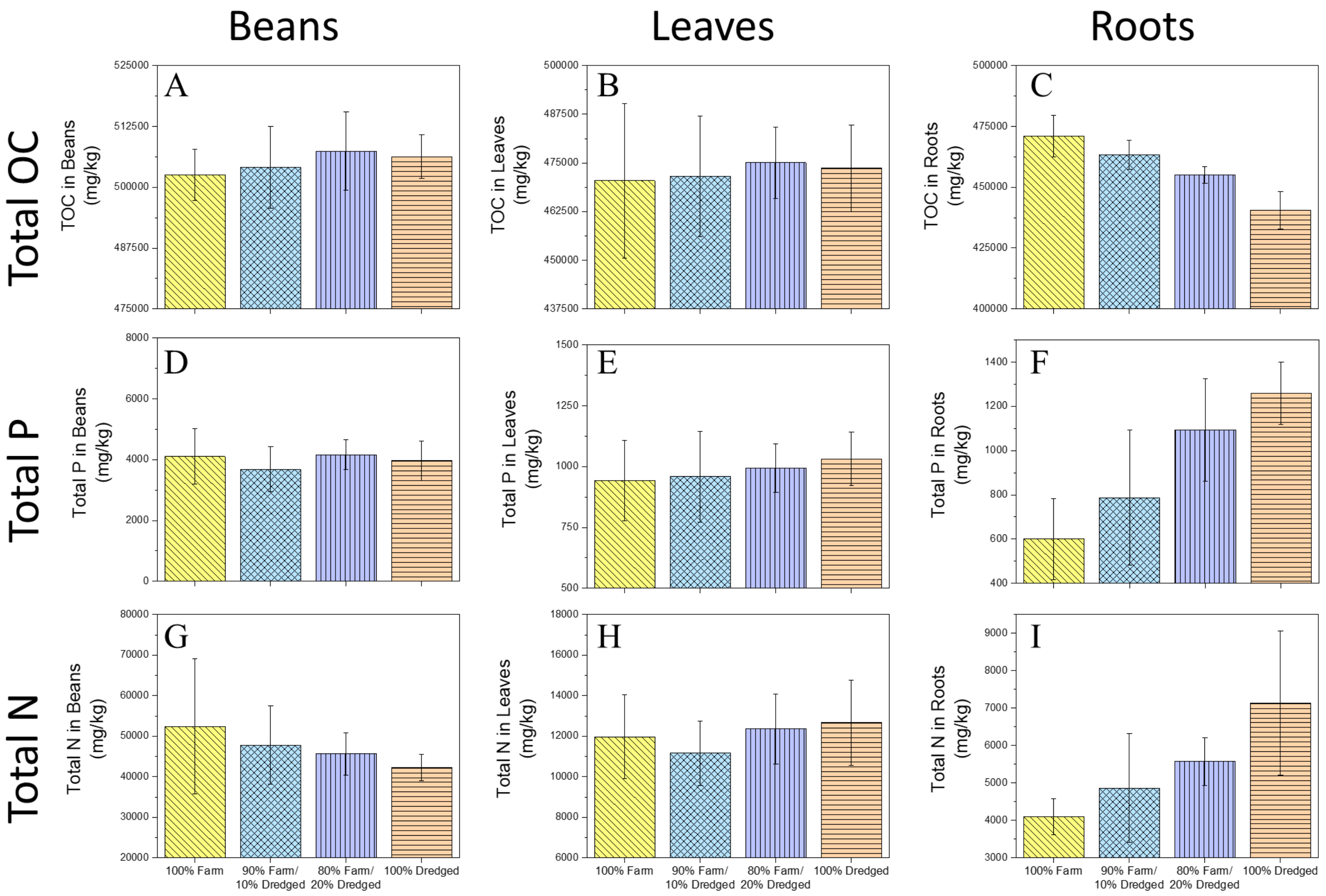


Figure 5. TOC, TP and TN concentrations in soybean, leaves and roots as a function of various dredged sediment ratios with and without soybean.

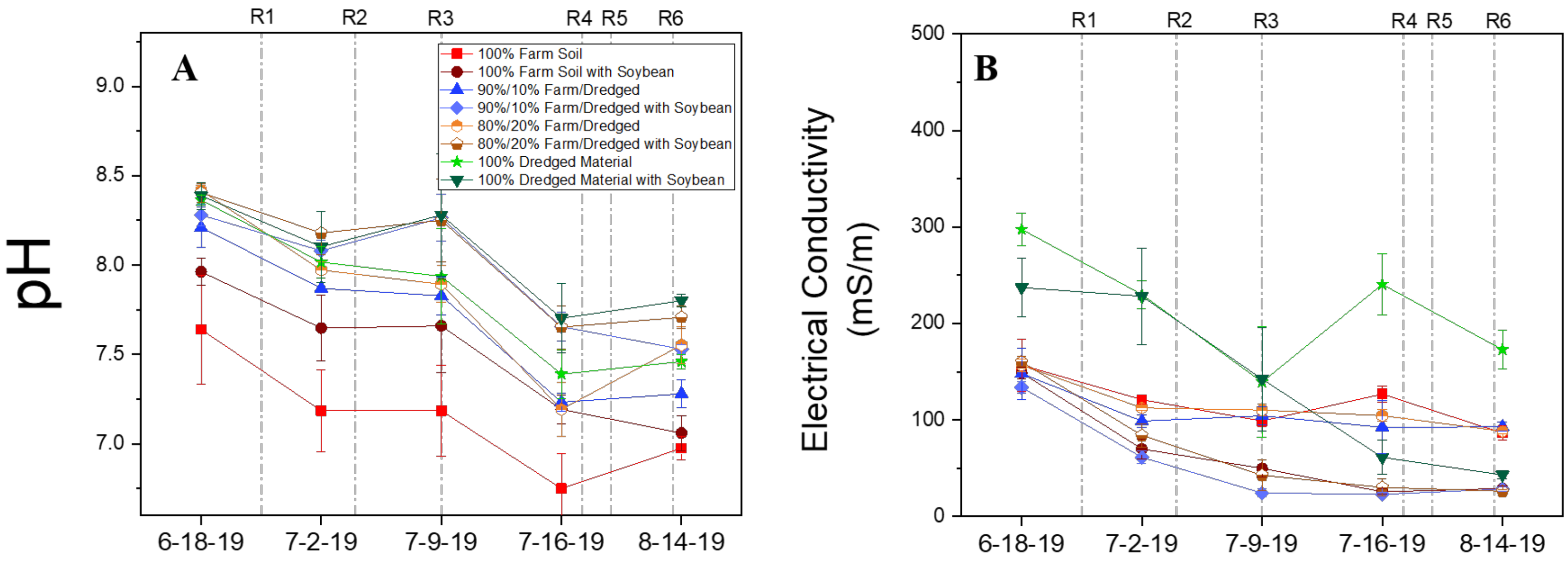


Figure 6. pH (A) and electrical conductivity (B) in percolated solutions after induced rainfall events as a function of various dredged sediment ratios with and without soybean.

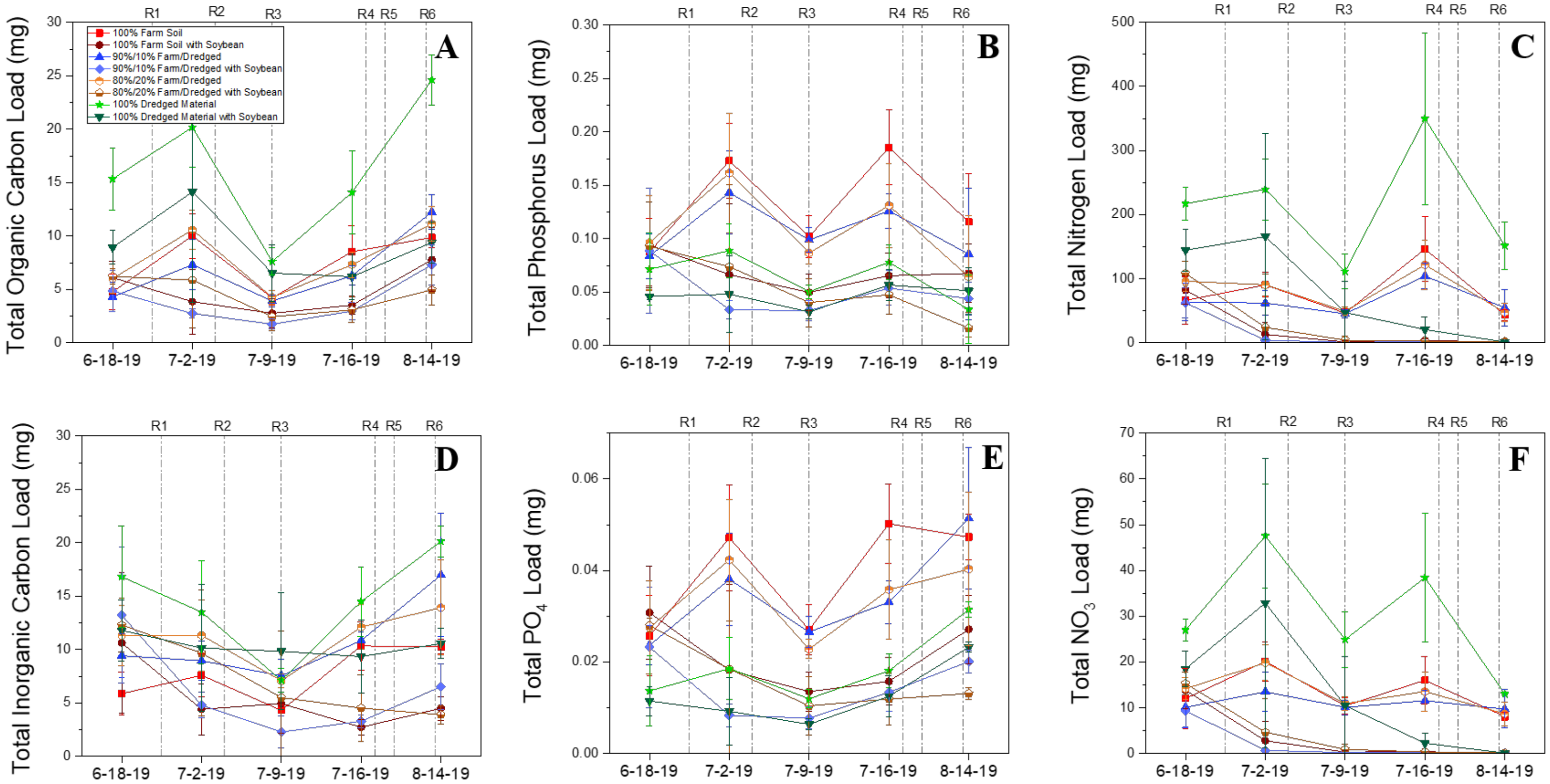


Figure 7. TOC (A), TP (B), TN (C), TIC (D), total PO4 (E), and total NO3 (F) loads in percolated solutions as a function of various dredged sediment ratios with and without soybean.

APPENDIX C: SUPPLEMENTAL INFORMATION

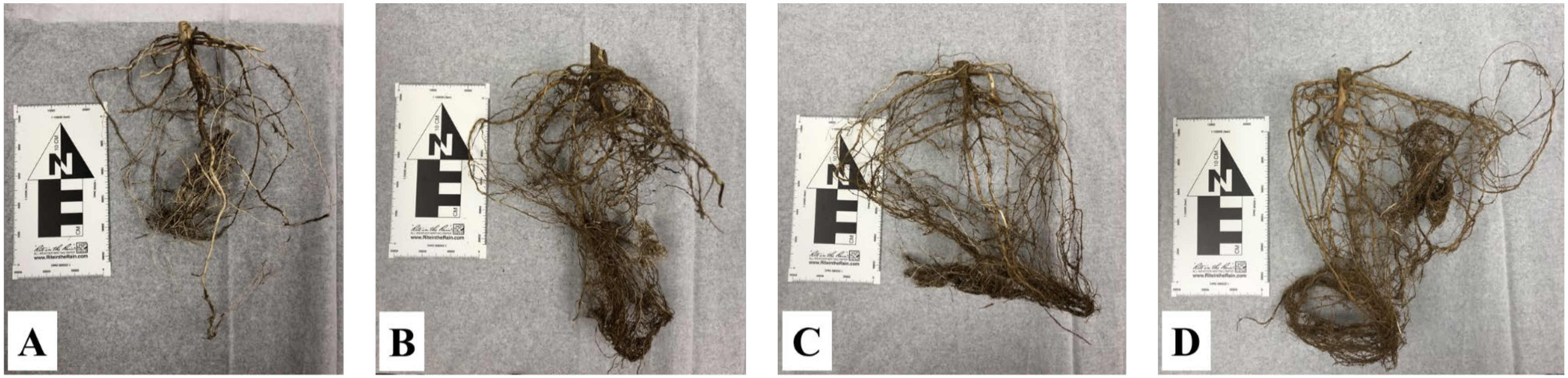


Figure S1. Soybean root systems examples for 100% farm soil (A), 90% farm soil/10% dredged sediment (B), 80% farm soil/20% dredged sediment (C) and 100% dredged sediment (D). Root distribution was limited by bucket size. The roots shown, have been placed in paper bags for transport to the lab and not straightened to their full extent. Smaller roots and root hairs were bundled or rolled for manageable placement in the bags.

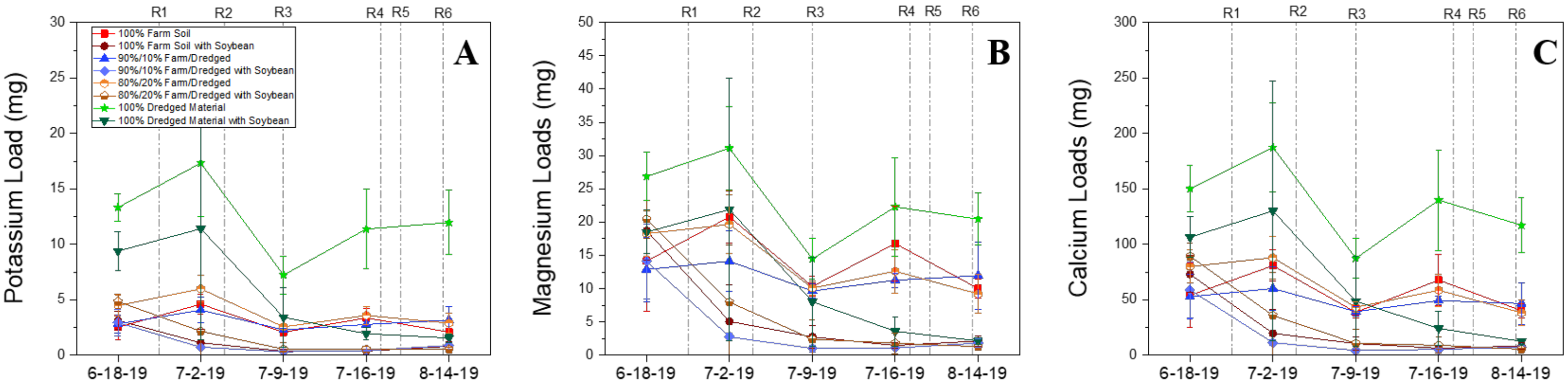
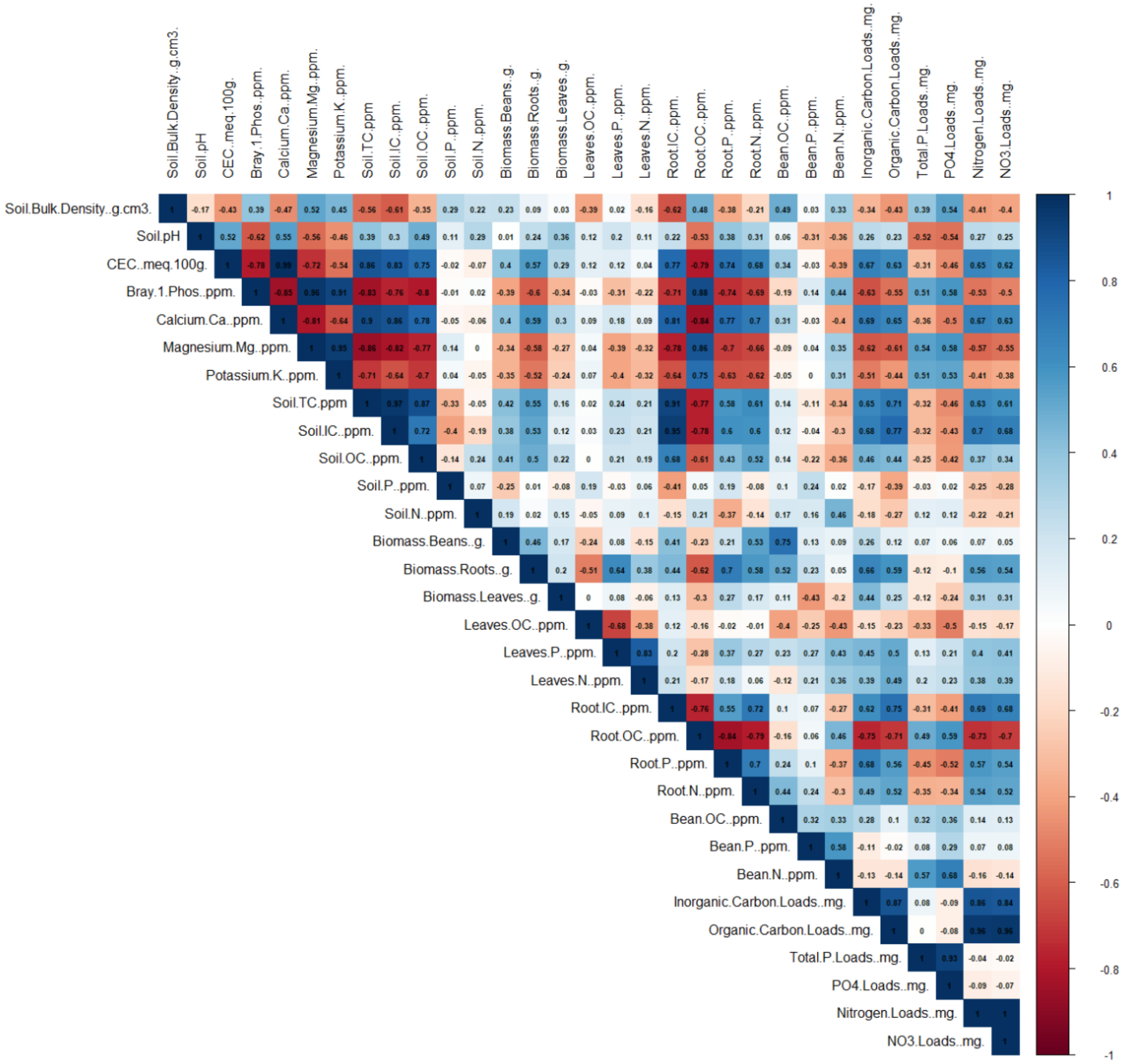
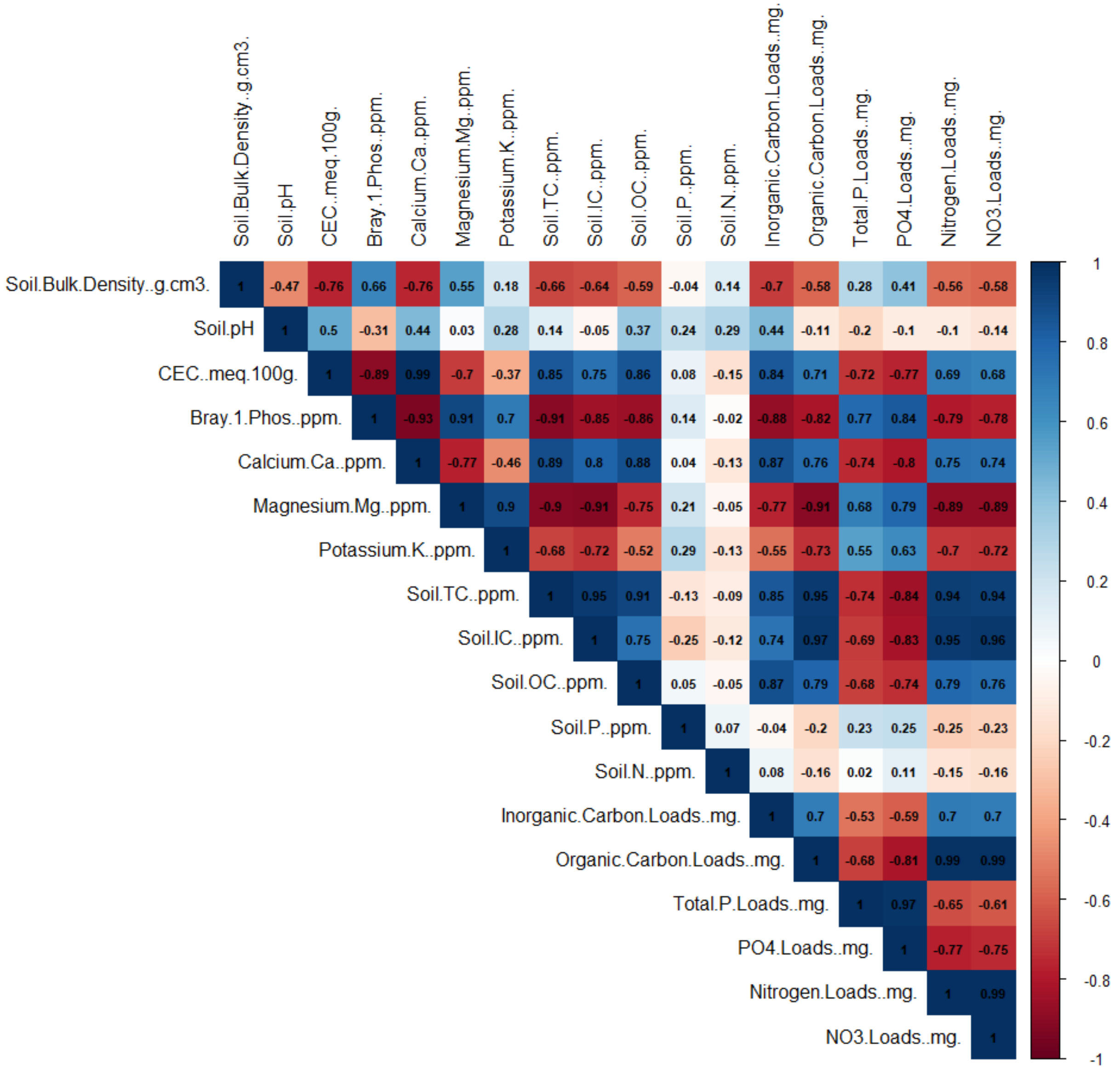


Figure S2. Potassium (A), magnesium (B), and calcium (C) loads in percolated solutions as a function of various dredged sediment ratios with and without soybean.



	Soil.Bulk.Density..g.cm3.	Soil.pH	CEC..meq.100g.	Bray.1.Phos..ppm.	Calcium.Ca..ppm.	Magnesium.Mg..ppm.	Potassium.K..ppm.	Soil.TC.ppm	Soil.IC..ppm.	Soil.OC..ppm.	Soil.P..ppm.	Soil.N..ppm.	Biomass.Beans..g.	Biomass.Roots..g.	Biomass.Leaves..g.	Leaves.OC..ppm.	Leaves.P..ppm.	Leaves.N..ppm.	Root.IC..ppm.	Root.OC..ppm.	Root.P..ppm.	Root.N..ppm.	Bean.OC..ppm.	Bean.P..ppm.	Bean.N..ppm.	Inorganic.Carbon.Loads..mg.	Organic.Carbon.Loads..mg.	Total.P.Loads..mg.	PO4.Loads..mg.	Nitrogen.Loads..mg.	NO3.Loads..mg.
Soil.Bulk.Density..g.cm3.	1	-0.17	-0.43	0.39	-0.47	0.52	0.45	-0.56	-0.61	-0.35	0.29	0.22	0.23	0.09	0.03	-0.39	0.02	-0.16	-0.62	0.48	-0.38	-0.21	0.49	0.03	0.33	-0.34	-0.43	0.39	0.54	-0.41	-0.4
Soil.pH		1	0.52	-0.62	0.55	-0.56	-0.46	0.39	0.3	0.49	0.11	0.29	0.01	0.24	0.36	0.12	0.2	0.11	0.22	-0.53	0.38	0.31	0.06	-0.31	-0.36	0.26	0.23	-0.52	-0.54	0.27	0.25
CEC..meq.100g.			1	-0.78	0.99	-0.72	-0.54	0.86	0.83	0.75	-0.02	-0.07	0.4	0.57	0.29	0.12	0.12	0.04	0.77	-0.79	0.74	0.68	0.34	-0.03	-0.39	0.67	0.63	-0.31	-0.46	0.65	0.62
Bray.1.Phos..ppm.				1	-0.85	0.96	0.91	-0.83	-0.76	-0.8	-0.01	0.02	-0.39	-0.6	-0.34	-0.03	-0.31	-0.22	-0.71	0.88	-0.74	-0.69	-0.19	0.14	0.44	-0.63	-0.55	0.51	0.58	-0.53	-0.5
Calcium.Ca..ppm.					1	-0.81	-0.64	0.9	0.86	0.78	-0.05	-0.06	0.4	0.59	0.3	0.09	0.18	0.09	0.81	-0.84	0.77	0.7	0.31	-0.03	-0.4	0.69	0.65	-0.36	-0.5	0.67	0.63
Magnesium.Mg..ppm.						1	0.95	-0.86	-0.82	-0.77	0.14	0	-0.34	-0.58	-0.27	0.04	-0.39	-0.32	-0.78	0.86	-0.7	-0.66	-0.09	0.04	0.35	-0.62	-0.61	0.54	0.58	-0.57	-0.55
Potassium.K..ppm.							1	-0.71	-0.64	-0.7	0.04	-0.05	-0.35	-0.52	-0.24	0.07	-0.4	-0.32	-0.64	0.75	-0.63	-0.62	-0.05	0	0.31	-0.51	-0.44	0.51	0.53	-0.41	-0.38
Soil.TC.ppm								1	0.97	0.87	-0.33	-0.05	0.42	0.55	0.16	0.02	0.24	0.21	0.91	-0.77	0.58	0.61	0.14	-0.11	-0.34	0.65	0.71	-0.32	-0.46	0.63	0.61
Soil.IC..ppm.									1	0.72	-0.4	-0.19	0.38	0.53	0.12	0.03	0.23	0.21	0.95	-0.78	0.6	0.6	0.12	-0.04	-0.3	0.68	0.77	-0.32	-0.43	0.7	0.68
Soil.OC..ppm.										1	-0.14	0.24	0.41	0.5	0.22	0	0.21	0.19	0.68	-0.61	0.43	0.52	0.14	-0.22	-0.36	0.46	0.44	-0.25	-0.42	0.37	0.34
Soil.P..ppm.											1	0.07	-0.25	0.01	-0.08	0.19	-0.03	0.06	-0.41	0.05	0.19	-0.08	0.1	0.24	0.02	-0.17	-0.39	-0.03	0.02	-0.25	-0.28
Soil.N..ppm.												1	0.19	0.02	0.15	-0.05	0.09	0.1	-0.15	0.21	-0.37	-0.14	0.17	0.16	0.46	-0.18	-0.27	0.12	0.12	-0.22	-0.21
Biomass.Beans..g.													1	0.46	0.17	-0.24	0.08	-0.15	0.41	-0.23	0.21	0.53	0.75	0.13	0.09	0.26	0.12	0.07	0.06	0.07	0.05
Biomass.Roots..g.														1	0.2	-0.51	0.64	0.38	0.44	-0.62	0.7	0.58	0.52	0.23	0.05	0.66	0.59	-0.12	-0.1	0.56	0.54
Biomass.Leaves..g.															1	0	0.08	-0.06	0.13	-0.3	0.27	0.17	0.11	-0.43	-0.2	0.44	0.25	-0.12	-0.24	0.31	0.31
Leaves.OC..ppm.																1	-0.68	-0.38	0.12	-0.16	-0.02	-0.01	-0.4	-0.25	-0.43	-0.15	-0.23	-0.33	-0.5	-0.15	-0.17
Leaves.P..ppm.																	1	0.83	0.2	-0.28	0.37	0.27	0.23	0.27	0.43	0.45	0.5	0.13	0.21	0.4	0.41
Leaves.N..ppm.																		1	0.21	-0.17	0.18	0.06	-0.12	0.21	0.36	0.39	0.49	0.2	0.23	0.38	0.39
Root.IC..ppm.																			1	-0.76	0.55	0.72	0.1	0.07	-0.27	0.62	0.75	-0.31	-0.41	0.69	0.68
Root.OC..ppm.																				1	-0.84	-0.79	-0.16	0.06	0.46	-0.75	-0.71	0.49	0.59	-0.73	-0.7
Root.P..ppm.																					1	0.7	0.24	0.1	-0.37	0.68	0.56	-0.45	-0.52	0.57	0.54
Root.N..ppm.																						1	0.44	0.24	-0.3	0.49	0.52	-0.35	-0.34	0.54	0.52
Bean.OC..ppm.																							1	0.32	0.33	0.28	0.1	0.32	0.36	0.14	0.13
Bean.P..ppm.																								1	0.58	-0.11	-0.02	0.08	0.29	0.07	0.08
Bean.N..ppm.																									1	-0.13	-0.14	0.57	0.68	-0.16	-0.14
Inorganic.Carbon.Loads..mg.																										1	0.87	0.08	-0.09	0.86	0.84
Organic.Carbon.Loads..mg.																											1	0	-0.08	0.96	0.96
Total.P.Loads..mg.																												1	0.93	-0.04	-0.02
PO4.Loads..mg.																													1	-0.09	-0.07
Nitrogen.Loads..mg.																														1	1
NO3.Loads..mg.																															1

Figure S3. Physicochemical correlations between soybean, soils and percolated solutions. Strong correlations appeared as dark blue (positive correlation) or dark red (negative correlation). The lighter colors showed weaker correlations. Correlation values are included for each square.



	Soil.Bulk.Density..g.cm3.	Soil.pH	CEC..meq.100g.	Bray.1.Phos..ppm.	Calcium.Ca..ppm.	Magnesium.Mg..ppm.	Potassium.K..ppm.	Soil.TC..ppm.	Soil.IC..ppm.	Soil.OC..ppm.	Soil.P..ppm.	Soil.N..ppm.	Inorganic.Carbon.Loads..mg.	Organic.Carbon.Loads..mg.	Total.P.Loads..mg.	PO4.Loads..mg.	Nitrogen.Loads..mg.	NO3.Loads..mg.
Soil.Bulk.Density..g.cm3.	1	-0.47	-0.76	0.66	-0.76	0.55	0.18	-0.66	-0.64	-0.59	-0.04	0.14	-0.7	-0.58	0.28	0.41	-0.56	-0.58
Soil.pH		1	0.5	-0.31	0.44	0.03	0.28	0.14	-0.05	0.37	0.24	0.29	0.44	-0.11	-0.2	-0.1	-0.1	-0.14
CEC..meq.100g.			1	-0.89	0.99	-0.7	-0.37	0.85	0.75	0.86	0.08	-0.15	0.84	0.71	-0.72	-0.77	0.69	0.68
Bray.1.Phos..ppm.				1	-0.93	0.91	0.7	-0.91	-0.85	-0.86	0.14	-0.02	-0.88	-0.82	0.77	0.84	-0.79	-0.78
Calcium.Ca..ppm.					1	-0.77	-0.46	0.89	0.8	0.88	0.04	-0.13	0.87	0.76	-0.74	-0.8	0.75	0.74
Magnesium.Mg..ppm.						1	0.9	-0.9	-0.91	-0.75	0.21	-0.05	-0.77	-0.91	0.68	0.79	-0.89	-0.89
Potassium.K..ppm.							1	-0.68	-0.72	-0.52	0.29	-0.13	-0.55	-0.73	0.55	0.63	-0.7	-0.72
Soil.TC..ppm.								1	0.95	0.91	-0.13	-0.09	0.85	0.95	-0.74	-0.84	0.94	0.94
Soil.IC..ppm.									1	0.75	-0.25	-0.12	0.74	0.97	-0.69	-0.83	0.95	0.96
Soil.OC..ppm.										1	0.05	-0.05	0.87	0.79	-0.68	-0.74	0.79	0.76
Soil.P..ppm.											1	0.07	-0.04	-0.2	0.23	0.25	-0.25	-0.23
Soil.N..ppm.												1	0.08	-0.16	0.02	0.11	-0.15	-0.16
Inorganic.Carbon.Loads..mg.													1	0.7	-0.53	-0.59	0.7	0.7
Organic.Carbon.Loads..mg.														1	-0.68	-0.81	0.99	0.99
Total.P.Loads..mg.															1	0.97	-0.65	-0.61
PO4.Loads..mg.																1	-0.77	-0.75
Nitrogen.Loads..mg.																	1	0.99
NO3.Loads..mg.																		1

Figure S4. Physicochemical correlations between soils and percolated solutions. Strong correlations appeared as dark blue (positive correlation) or dark red (negative correlation). The lighter colors showed weaker correlations. Correlation values are included for each square.