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Returning Degraded Soils to Productivity: an Examination of the Potential of Coarse Woody Amendments for Improved Water Retention and Nutrient Holding Capacity

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Abstract Soil degradation and desertification from agricultural land use is a serious and growing problem worldwide. Bringing degraded soils back into production is crucial to stop the cycle of land degradation, followed by abandonment and a subsequent shift of agricultural pressure to previously uncultivated soils. To return degraded and desertified landscapes to productivity, sandy soils must first be improved to enhance water and nutrient holding capacity. In this study we examine the ability of incorporated coarse woodchips to alter water holding capacity in very sandy, degraded soils in the field, complemented by soil column experiments in the laboratory examining the mechanisms behind changes in water retention. In the second phase of our lab studies, we examined nutrient losses, both soluble and gaseous, from laboratory-scale soil columns under different fertilization application regimes. Coarse woodchips incorporated into the soil increased water holding capacity by 16% in the field and 18% in the laboratory which was attributed to absorption of water by the woodchips, with limited evidence of the occurrence of flow path disruption. Soluble nutrient losses of nitrogen (N) and phosphorus (P) were smallest when fertilizer was applied in liquid form, as opposed to incorporated or surface-applied dry granules. Carbon dioxide emissions increased by 200% in the presence of woodchips, likely due to increased respiration by the microbial biomass. This study suggests that incorporating coarse wood chips into the soil is a viable strategy for increasing water and nutrient retention in very sandy and degraded soils and can provide a basis for enhancing ecological processes. More work is needed to examine whether increased water retention by woodchips also increases the availability of water and nutrients to plants.

Keywords Soil restoration · Soil amendment · Water quality · Greenhouse gases · Agriculture · Nutrient pollution · Fertilizers · Eutrophication

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1 Introduction

Soils around the world have been degraded by agricultural practices and chronic soil mismanagement (Bridges and Oldeman 1999; Oyarzun et al. 2007). The growing human population and concomitant intensification of agriculture has led to continuous cultivation and plowing of increasingly larger swaths of land. As soils are plowed, organic matter is lost in two primary ways. The first pathway of loss is to the atmosphere as carbon dioxide (CO_2) through microbial respiration. Through the mechanical process of turning the soil, oxygen, an important component of respiration, is introduced into the soil, and soil aggregates are broken up to reveal carbon (C) compounds that previously were isolated from microbial activity (Barnwell et al. 1992; Reicosky et al. 1997). Loss of organic matter can also occur when agricultural soils are frequently plowed and soil particles are carried away by wind and water erosion (Lal 2003). These losses can reduce a soil's productivity and, in extreme cases, initiate the process of desertification (D'Odorico et al. 2013). Subsequently, unproductive soils are often abandoned, leading to the conversion of more land plowed for cultivation, thus feeding a vicious cycle of land use and degradation.

As a major contributor to soil health, organic matter plays an important role in the ability of a soil to retain water, and its loss can have compounding effects. It is well established that soil organic matter increases water holding capacity and, subsequently, plant available water capacity (Hudson 1994). Among other properties, increased organic matter can result in larger pore spaces as soil aggregates form, creating more spaces for the water to occupy (Larney and Angers 2012). Water is also absorbed into the components of organic matter itself after a rain event and released back into the soil matrix as the system dries (Lyon and Buckman 1943). In addition, organic matter increases infiltration capacity, and can create flow pathways allowing rainwater to move more quickly into the matrix of the soil, avoiding surface runoff generation and subsequent loss from the system. All told, chronic loss of organic matter is one of the key drivers of degradation of agricultural soils.

With the intensification of agriculture, the loss of nutrients has come a steady escalation in fertilizer use, resulting in a global increase in excess of 700% in the past few decades (Foley et al. 2005). Loss of organic matter can diminish the ability of soils to retain nutrients, because a primary mechanism of retention is through cation exchange capacity (Larney and Angers 2012), which is greater in organic matter than the surrounding mineral soil. Accordingly, an increase in organic matter in the soil contributes to increased cation exchange capacity (Parfitt et al. 1995). Conversely, the inability of the degraded soil to retain excess nitrogen (N) and phosphorus (P) from fertilizers can cause eutrophication and hypoxia in estuarine and fresh water systems, respectively (Bouwman et al. 2002; Carpenter et al. 1998). These and other excess nutrients enter adjacent surface water bodies via precipitation (wet deposition), surface runoff, leaching, and groundwater return flows.

While the presence of sufficient organic matter is important to note when determining the capacity of soils to retain nutrients, the method by which fertilizers are applied is also an important consideration. To reduce losses of soluble nutrients from fertilized land, it is recommended that fertilizers be incorporated into the soil in a dry form (Roberts 2007). Incorporation reduces losses from surface runoff, while dry fertilizers reduce losses by slowing the release of nutrients and reducing immediate losses through preferential flow pathways.

Along with soluble losses of nutrients, it is important to consider the likelihood of gaseous losses. Agricultural land is a significant contributor to greenhouse gas (GHG) emissions, contributing to the changing global climate through the degradation of soils and an increase in fluxes (Oertel et al. 2016; Smith et al. 2008). Plowed and aerated soil not only increases availability of C, which is respired and emitted as CO_2 by soil microbes, but also yields production of nitrous oxide (N_2O) by soil microorganisms through incomplete denitrification. Indeed, N fertilizers provide the necessary substrate to stimulate denitrification and subsequent N_2O production (McSwiney and Robertson 2005).

Although increased fertilizer can help sustain crop yields, chronic degradation of soils often ultimately leads to abandonment of farmlands. One strategy for combating soil degradation, reclaiming soils, and halting the cycle of degradation and abandonment is the use of organic amendments, which add both organic matter and nutrients and have proven more effective in improving soil properties than adding nutrients alone (Gardner et al. 2010). Historically, the most commonly employed organic amendments are manure, green manures, and compost, all materials that are nutrient rich and easily degradable by soil microbes (Larney and Angers 2012). As a result, they need to be applied at regular intervals to maintain the benefits of the amendment. More recently, organic amendments with longer-term stability in the soil have included biochar and industrial wastes (Gardner et al. 2010; Kasongo et al. 2011; Laird et al. 2010).

An area of interest in our studies is the use of woody materials, which could be used as a stable source of organic matter that would improve soil structure for an extended period of time. In a number of settings, woodchips are used as a surface mulch for ecosystem restoration (Fang et al. 2011; Ferrini et al. 2008; Głąb and Kulig 2008; Buchanan et al. 2002; Prats et al. 2012) and have been used as media for denitrifying bioreactors (Ghane et al. 2014, 2016; Pluer et al. 2016). In addition, sawdust can be used to "reverse fertilize," to immobilize N, and to reduce soluble losses, in situations where soils have become overly N rich (Bugbee 1999). However, there are limited instances in the literature in which woodchips have been incorporated into the soil. In one example, Meffe et al. (2016), soil columns were used to examine the impact of incorporated woodchips on vegetative buffer strips used to treat household wastewater. Incorporated woodchips resulted in higher volumetric water content (VWC) and lower rates of N losses, compared with woodchips applied on the surface.

We propose that restoring severely degraded soils in a sustainable way will require an input of stable organic material that can impart benefits on a time scale of many years. To that end, we expect the incorporation of coarse woodchips, those larger than 5 mm in all dimensions, to behave similarly to other organic amendments that have been previously studied (Ajwa and Tabatabai 1994; Dempster et al. 2012; Fueki et al. 2012; Hudson 1994; Khaleel et al. 1981; Larney and Angers 2012; Li et al. 2018), improving soil health by enhancing structure and facilitating important functions, while resisting rapid decomposition. In this study, we investigated two facets of the use of incorporated coarse woodchips as a soil reclamation strategy for very sandy, degraded soil. First, we investigated the ability of incorporated coarse woodchips to increase water holding capacity of sandy soils in the field and followed up by examining mechanisms driving the changes using soil columns in the laboratory. Second, using the soil columns, we quantified both soluble and gaseous losses of N and P applied as wet and dry fertilizers to determine best practices to reduce nutrient losses from fertilizers applied in conjunction with incorporated coarse woodchips. We hypothesized that (1) coarse woodchips will increase water holding capacity of sandy soils and that (2) dry fertilizers will generate less soluble nutrient loss because nutrient releases into the soil are slower than for dissolved fertilizers.

2 Materials and Methods

This study was an extension of an ongoing project conducted in the Ningxia province of China, a region that has experienced severe grassland degradation due to agricultural conversion (for review, see Li et al. 2018). Thousands of years of agriculture in northern China have left vast expanses of severely degraded sandy soils where few plants can grow without irrigation. Historical evidence, i.e., petroglyphs from nearby Helan Mountains, suggests that these landscapes once were productive grasslands, despite limited rainfall in the region. The overarching aim of our research is to develop an intervention to improve the ability of the soils in the region to capture more of the limited rainfall. As a complement to the research in Ningxia, we chose an additional site in the northern Great Plains of North America for comparable experimentation: the US Department of Agriculture (USDA) Northern Great Plains Research Laboratory (NGPRL), which is part of the Long-term Agroecosystem Research (LTAR) network located near Mandan, North Dakota (ND), USA (latitude 46° 48′ 38″ N, longitude 100° 54′ 35″ W). This present-day grassland site in the northern USA was selected for experimentation for several reasons. First, it also is a grassland that has been altered from its original state, although it is much earlier on in the degradation process. Importantly, it has a climate very similar to Ningxia, although, the site in Mandan receives slightly more precipitation, with an annual pattern similar to that observed in Ningxia (Fig. 1a). In general, Ningxia mean temperatures are approximately 10 °C higher than Mandan, but mean high and low monthly temperatures in both locations follow nearly identical annual patterns and are very similar in magnitude of change (Fig. 1b). Weather data were obtained from the National Oceanic and Atmospheric Association (NOAA) Global Historical Climatology Network (GHCN) of weather stations, using the meteorological station (Number USC00325479) located at the NGPRL in Mandan, ND (NOAA 2015). Weather data from Ningxia, China were obtained from an onsite weather station. Soils found in each location have similar

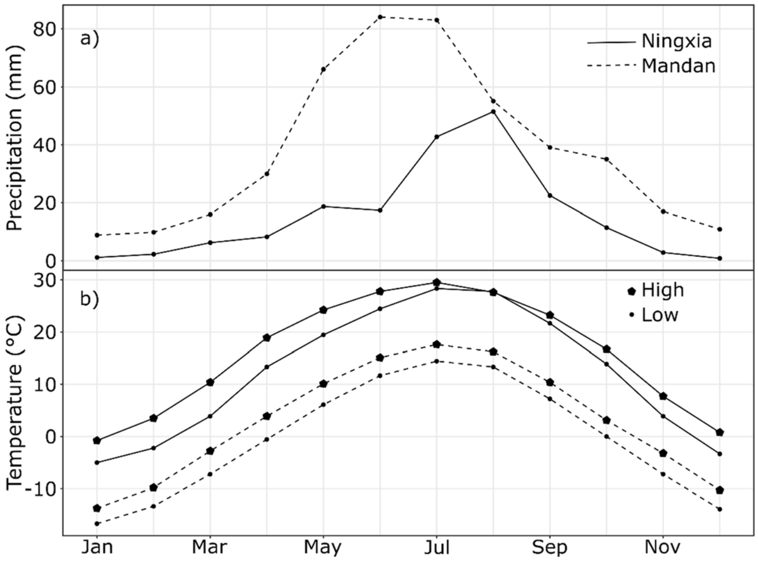

Fig. 1 Mean monthly precipitation in mm (a) and high and low temperatures in degrees Celsius (b). Solid lines represent data from Ningxia, while dotted lines are data from Mandan. High and low monthly mean temperatures are denoted by pentagons and circles, respectively

textures, with soils from Ningxia classified as sand with 93.8% sand, 2.6% silt, and 3.6% clay and the Tally-Parshall soils from Mandan were classified as a sandy loam with 70.3% sand, 18.3% silt, and 11.4% clay. Soils found in Ningxia, however, are very low in organic matter, by the loss on ignition method, reporting only 0.1% organic matter, while soils from the Mandan site have 2.67% organic matter. Both locations are historical grasslands, the differences in organic matter are indicative of the comparative severity of soil degradation in each location.

2.1 Field Experiment

In the first phase of this study, a field experiment was implemented at the NGPRL near Mandan to evaluate water holding capacity of soils when amended with incorporated woodchips. Six plots, 0.5 m by 1 m, were established, and three plots were selected at random and then amended by incorporating woodchips into the soil manually at 20% by volume, to a depth of 20 cm, i.e., woodchip treatment (WCT). The soil to woodchip ratio is higher than that tested by Li et al. (2018) to amplify the response from the woodchips in soil less degraded than that examined in Li et al. (2018). The depth of the amendment was determined based on common plow depth; if the amendment were to be applied on a large scale, it could be incorporated using existing farm equipment. Quaking Aspen (*Populus tremuloides*) woodchips were obtained from trees in the Finger Lakes Region of New York and processed into woodchips by the second author. This species was chosen as it is the closest relative of the White Poplar (*Populus alba*), abundant in the Ningxia province of China, that was readily available in the Finger Lakes region of New York. The woodchips were sieved with a 5-mm sieve to eliminate fine materials, and larger pieces were eliminated to reduce the variability of the dimensions. The length of the woodchips varied from 0.61 to 3.80 cm, with a mean length of 1.60 cm. The other three plots were used as a control: the soil was manually mixed in the same fashion as the treatment plots but did not receive any amendment. In each plot, soil moisture data loggers (Decagon Devices) were installed at a depth of 10 cm and soil moisture was recorded every 30 min for 60 days from June 18 to August 17, 2015. Simultaneous meteorological data were obtained from a NGPRL weather station located near the study site.

In order to detect differences in water holding capacity, our analyses focused mainly on the 48-h period immediately following rain events with precipitation amounts greater than 5 mm. One event in late July was omitted from this analysis because it was highly localized and did not generate a response from all test plots. In the 48-h period following the rain events, we quantified the rate at which the soil dried by calculating the slope of the line between the maximum and the minimum VWC values that occurred in the 48-h period following the storm. To determine differences between maximum and minimum VWCs, as well as the rate of drying between treatment and control plots, we used linear mixed models with fixed effects and random effects. Linear mixed models were also used to examine the relationships between the magnitude of a given storm and the response variables. Data processing and statistical analyses were conducted using R v3.0.2.

2.2 Lab Soil Columns Experiments

2.2.1 Mechanisms of Water Retention

In subsequent laboratory experiments, soil columns were used to examine the relative influence of two physical processes, absorption and flow path disruption, on changes in water retention in woodchip-amended soils. Columns were constructed from rigid polyvinyl chloride (PVC) pipes, 10.16 cm in diameter, cut to a length of 35.5 cm, with a perforated cap attached to the bottom, and a mesh screen covering the openings to prevent soil loss. This column diameter is common in the literature when examining hydrological processes and nutrient transport (Khan and Jury 1990; Peters and Durner 2006; Zwingmann et al. 2009). Soil fill for the columns was a mixture of lab-grade sand and Tally-Parshall soil that was collected from the field plots at Mandan, ND. The two media were mixed to achieve a soil with a very sandy texture (87.1% sand, 10.6% silt, 2.3% clay) reflective of those observed in Ningxia, China (94% sand). Nine soil columns were constructed and separated equally into three treatments, with three replicates per treatment. As in the field, soil amendments were incorporated into the top 20 cm of the soil column. Due to the height of the columns, and to limit empty space at the top of the columns, all columns were first filled with 5 cm of the base soil on the bottom. The top 20 cm of the column was then filled with one of three treatments: base soil mixed with 10% by volume oven-dried woodchips from the tree species *Populus tremuloides* (WCT); base soil with 10% by volume shredded rubber mulch (Rubberific® Premium) (rubber mulch treatment, RMT); or base soil only (control). The ratio of soil to the amendment was chosen based on results from Li et al. (2018), which determined a 10% by volume woodchip amendment resulted in the highest water holding capacity. Woodchip dimensions were achieved with the same methodology as described previously and the rubber mulch amendment was treated in the same way to ensure consistent texture among treatments. Rubber mulch was chosen as a means to determine the effect of flow path disruption by eliminating the possibility of retention by absorption. All amendments were mixed manually into the soil and then poured into the column. Due to the high sand content of the soil, it was easily poured into the columns and did not require incremental compaction as is common in soil column experiments. During filling, bulk densities for the control columns and the woodchip-amended columns similar to those observed by Li et al. (2018) were achieved. We determined bulk density by dividing the mass of the soil fill by the volume of the columns. Dry bulk density in the control columns was 1.53 g/cm^3, and dry bulk density in the woodchip-amended columns was 1.13 g/cm^3. We recognize the importance of bulk density in water and nutrient retention and acknowledge that the difference in bulk density imposed by our treatments is a potential confounding factor on our measured outcomes. However, we would like to note that changing soil characteristics, such as bulk density, is part of the goals of the project to improve soil characteristics resulting in increased water and nutrient retention. To account for this difference, we compared treatments by unit volume, the filled columns, rather than using the more common method of normalizing by mass. From bulk density, we estimated porosity of the control soils by assuming a particle density of silica sand, 2.65 g/cm^3. Thus, the porosity of our control soils was 42.3% and the total volume of voids was 830.9 mL.

After filling the columns with soil, 100 mL of deionized water was added to each. This was equivalent to a 1.2 cm rain event and represented 12% of the soil pore volume in the control treatment. Columns were then left for approximately 24 h to allow time for the sand to settle and to allow for an initial wetting period of the media in the column. Columns were then subjected to three consecutive simulated rain events, with 7 (± 3) days between each event. The majority of rain events occurred 7 (± 1) days from the previous event, but on rare occasions unforeseen conflicts forced slightly shorter or longer inter-rain periods. Rain events were consistent with an expected 5-year storm in Mandan, ND, with a volume of 535 mL, or 65.99 mm (NOAA 2017). This sizeable storm magnitude was chosen to ensure the generation of leachate and to amplify the impacts of the treatments. Water that leached from each column was collected at high temporal resolution, 30 second intervals, until drainage had largely ceased, a period lasting between 5 and 8 min. The total quantity of water lost from the columns was recorded. A linear mixed model with fixed and random effects, as well as a one-way ANOVA, were used to determine significant differences between water retained by each treatment over the course of the three rain events.

2.2.2 Nutrient Losses from Fertilizers

A similar column experiment was used to evaluate and compare losses from directed fertilization in the presence or absence of incorporated woodchips. In this portion of the experiment, twenty-four soil columns were constructed and separated equally into two soil amendment treatments and four fertilizer treatments, with three replicates per combination of soil amendment and fertilizer. All columns were first filled with 5 cm of the same base soil used in the previous phase of the experiment. The top 20 cm of the column was then filled with one of two soil amendment treatments: base soil mixed with 10% by volume oven-dried woodchips from the tree species *Populus tremuloides* (WCT) or base soil only (control). The ratio of soil to woodchips was chosen based on results from Li et al. (2018), which determined 10% by volume resulted in the highest water holding capacity. Amendments were manually mixed into soils before fertilizer applications. Columns were then separated equally into four fertilizer treatments: 1) none—no fertilizer applied; 2) liquid—dry fertilizer was dissolved in the 100 mL of deionized water added during the setup phase; 3) dry incorporated—dry fertilizer was stirred into the dry soil before it was poured into the columns; and 4) dry surface—dry fertilizer was applied to the soil surface after filling had occurred before the 100 mL of deionized water was applied.

Columns that were fertilized each received 7.4 g P m^{-2} (74 kg P ha^{-1}) as dipotassium phosphate (K_2HPO_4) and 19.7 g N m^{-2} (197 kg N ha^{-1}) as potassium nitrate (KNO_3). Values were determined based on the upper limits of the recommended fertilization rates of prairie grasses (Kidd et al. 2017). After filling the columns, 100 mL of deionized water was added to each and rain events were simulated in the same manner as described in the *Mechanisms of Water Retention* methodological description.

At the beginning of the experiment, initial dry weights of the columns were recorded before any water was applied. Columns were then weighed during the experiment before and after each simulated rain event and every 24 h for 3 days after each rain event. Column dry weight was subtracted from wet weight to determine mass of the water retained which was then divided by the initial dry weight of the column to determine gravimetric water content (GWC). As described in the previous section, bulk densities similar to those reported by Li et al. (2018) were achieved. These values were used to convert GWC to VWC. In addition, gas flux samples were collected before and after each rain event to observe both ambient and post-rain gas fluxes. Water that leached from each column was collected after being allowed to freely drain for 1 hour, after all drainage had largely ceased. It is likely that drainage ceased after approximately 10 min, as with the previous experiment; however, we were examining cumulative effects and thus were not concerned with high-resolution temporal monitoring. The quantity of water lost from the columns was recorded, and water was immediately filtered using a 0.45-μm filter. Samples were then acidified to a $pH < 2$ and refrigerated until analysis. Water samples were analyzed for orthophosphate using the EPA method 365.1 (Heinonen and Lahti 1981) and for nitrate-nitrite using the EPA method 353.2 (O'Dell 1993). Linear mixed effects models with random and fixed effects were used to determine significant differences between VWCs. Student *t* tests were used to determine significant differences in N and P leachate losses with and without incorporated coarse woodchips.

To examine the influence of the treatments (i.e., soil amendment, fertilizer) and simulated rain events on GHG emissions, we determined fluxes of CO_2, N_2O, and methane (CH_4) from the columns using a static chamber method (Parkin and Venterea 2010). Sampling for GHGs was conducted before and after rain events; before each simulated rain event was applied, each column was fitted with an enclosed PVC cap with two septa for sampling as described by McPhillips et al. (2016). Four gas samples were taken from each column at 10-min intervals for a period of 30 min. This process was again repeated after the simulated rain event was completed. When water could no longer be observed standing on the soil surface, which occurred in a matter of seconds, the enclosed PVC cap was again fitted to the column and four gas samples were collected in the exact same manner as before the simulated rain event. Three pre-rain gas sampling efforts and three post-rain sampling efforts were conducted on each column, with an average of 7 (± 3) days between each event. All gas samples were analyzed for CO_2, N_2O, and CH_4 using an Agilent 6890 N gas chromatograph with a HP 7694 Headspace Autosampler, equipped with an electron capture detector and a flame ionization detector with a methanizer. We determined fluxes by fitting a linear model to the concentrations at the four time points sampled (0, 10, 20, and 30 min) and the ideal gas law allowed for conversion of volumetric to mass-based fluxes. Only flux calculations with an r-squared value of 0.75 or higher for CO_2 were included in the data analysis as is common with the static chamber method (Truhlar et al. 2016). A linear mixed effects model with fixed and random effects was used to examine significant predictors of fluxes. Student *t* tests were used to determine differences in samples taken from columns with and without incorporated coarse woodchips as well as before and after rain events. A one-way ANOVA was used to determine significant differences in gas fluxes under differing fertilization regimes.

3 Results and Discussion

3.1 Field Data

Results from soil moisture probes in the field soils of Mandan, ND from the summer of 2015 supported earlier studies (Li et al. 2018; Li et al. 2019a, 2019b) in which incorporated woodchips increased water holding capacity of sandy soils, as compared with control plots (Fig. 2). Over the course of the study period, approximately 150 mm of rain fell. To examine the soil moisture characteristics in response to rain events, we evaluated the four large (> 5 mm) precipitation events where a response was seen from all treatments. Chronologically, rainfall for the four events totaled 45 mm, 18 mm, 8 mm, and 20 mm. In the 48 h after each of the rain events, we examined three response variables: minimum VWC, maximum VWC, and the rate of drying (Fig. 3). Following the first rain event, during the drying phase, soil with incorporated woodchips had a higher mean minimum VWC than the control soil, with the effect becoming more pronounced with each successive rain event. A similar pattern was observed for maximum water content. We observe systematic differences indicating that soils with incorporated woodchips have increased water holding capacity, but, potentially due to low sample size, mean values were not significantly different. There was no significant difference in the rate of drying between the WCT and the control soils following a rain. Linear mixed models indicated that the rain event itself, a proxy for antecedent conditions, was a significant predictor for all three response variables. For the minimum VWC, the interaction between event and soil amendment was a significant predictor as well. A linear mixed model also revealed that the amount of precipitation in a rain event was not a significant predictor of maximum VWC or rate of drying after a rain event.

These findings indicate that the incorporation of woodchips into the soil influenced the minimum VWC following a storm. However, the magnitude of a given storm was not a significant predictor of the response, indicating that antecedent conditions or another factor are influencing the maximum VWC and rate of drying following storm events. The lack of statistical significance observed in what are clearly systematic differences might be attributable to the small sample size. Knighton and Walter (2016) similarly found that storm characteristics other than magnitude play important roles in hydrologic responses. Values for VWC observed in this woodchip experiment are consistent with those found in the literature for soils undergoing reclamation through other organic amendments (Khaleel et al. 1981; Kinney et al. 2012; Li et al. 2018; Meffe et al. 2016).

3.2 Lab Columns

3.2.1 Mechanisms of Water Retention

Water retention in WCT soil columns was significantly greater than in RMT columns after all three rain events, and significantly greater than control columns after the second and third rain events (Fig. 4). Water retention in rubber mulch–treated columns was lower and significantly different than the control columns only after rain event 1, but in rain events 2 and 3, RMT and control soils were not significantly different. The results from the first event likely reflected a wetting phase for all treatments. Control soils and woodchip-amended soils performed similarly in event 1 indicating that the woodchips were undergoing a wetting phase in which they were not yet effectively absorbing water, the woodchips diverged from the control soils after an initial wetting was complete, i.e., by the second rain event. It is possible that the rubber mulch, with virtually no absorption and a tendency towards hydrophobicity (Pelisser et al. 2011), created preferential flow pathways through the soil during this initial wetting phase, but the differences diminished after wetting, i.e., by the second rain event. In contrast, the significant differences in water

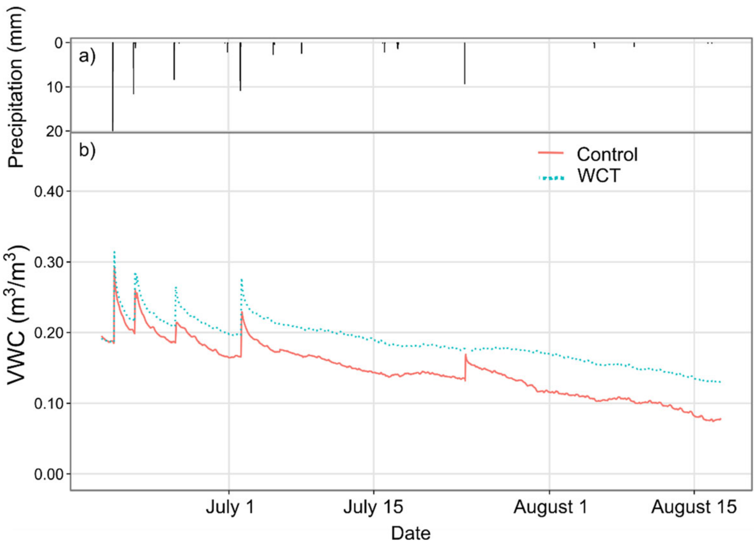

Fig. 2 Precipitation in mm (a) and mean volumetric water content (VWC) (b) measured over the summer of 2015 in Mandan, ND. The dotted blue line represents the woodchip treatment (WCT) plots and the solid pink line represents the control plots. Note: the y axis is in half hour intervals and as a result multiple precipitation bars may overlap

retention between the WCT and the RMT after all simulated rain events can be attributed to water absorption by the wood. The lack of difference between the control columns and the RMT columns in events 2 and 3 indicates that flow path disruption was not a significant contributor to the increased water retention observed in woodchip-amended soils; if it were, we would have expected to see increased retention in the RMT columns over the control columns. Therefore, we can attribute the differences in water retention between the WCT columns and all other treatments to absorption of water by the woodchips. Thus, we have identified the primary mechanism by which woodchips increase water holding capacity to be absorption by the woodchips and not flow path disruption.

A linear mixed model with fixed effects of treatment and rain event, and with random effects of column number indicated that treatment, rain event, and the interaction between the two, were significant predictors ($p < 0.05$) of water retention. Values for VWC in this experiment, which ranged between 3 and 14%, are consistent with those found in the above-described field-based experiment as well as in other reports in the literature (Khaleel et al. 1981; Kinney et al. 2012; Li et al. 2018; Meffe et al. 2016).

3.2.2 Soluble Nutrient Losses from Fertilizers

The subsequent experiment used to evaluate and compare losses from directed fertilization showed similar

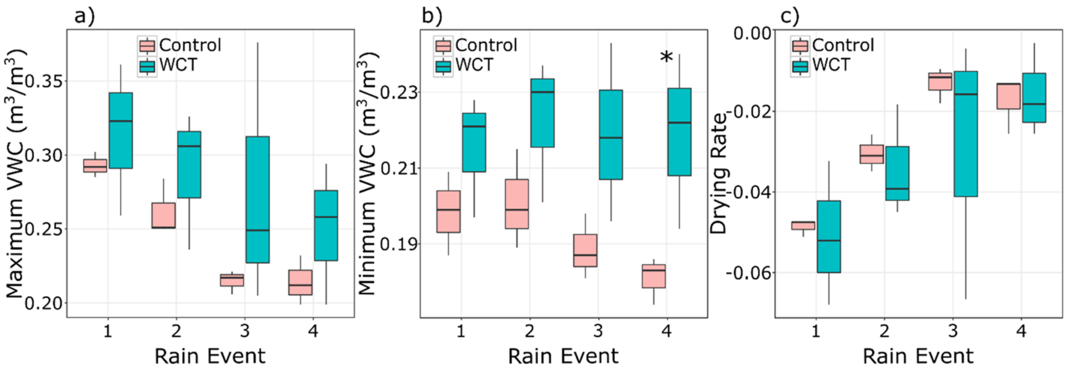

Fig. 3 Maximum (**a**) and minimum (**b**) volumetric water content (VWC) (m^3/m^3) as well as drying rate (change in VWC over time) (**c**) in the 48 h following each of the four large (> 5 mm) rain events which generated a response from all test plots. The dark (blue) boxes represent the woodchip treatment (WCT) plots while the lighter (pink) boxes represent the control plots. Mixed models with fixed effects of soil amendment and rain event and random effects of plot number were used to determine significance, * indicates significance at $p < 0.05$

patterns of absorption and retention of water by soils with incorporated woodchips (Figs. 3 and 4). Fertilized soils with incorporated woodchips displayed significantly higher VWCs than the fertilized control soils 48 h after each of the three simulated rain events (Fig. 5). Indeed, a linear mixed model, with fixed effects of soil amendment, and random effects of rain event, rain date, and column number, indicated that soil amendment was a significant ($p < 0.05$) predictor of VWC. This reinforced the findings in the previous two experiments, underscoring that incorporated woodchips increase water holding capacity of sandy soils.

Increased absorption and retention of water by woodchips was accompanied by the smallest losses of both soluble N and P from the columns when fertilizer was applied in a liquid form. In addition, when fertilizer was applied as a liquid and when it was applied in a dry surface application, there were significantly greater losses of soluble N from the control columns than from the woodchip-amended columns (Fig. 6). There also was greater loss of P in the control soil than in the WCT where liquid fertilizer was applied ($p = 0.06$), and the loss of P was significantly higher in the control soils where dry fertilizer was incorporated into the soil (Fig. 6). Overall, despite the better performance of woodchip-amended soil in reducing N and P losses in soil columns in some dry fertilizer applications, we conclude that nutrients should be applied in liquid form to soils with incorporated woodchips in order to limit the losses of both N and P. This finding runs counter to our original hypothesis and indicates that the potential for interaction with woodchips is more influential in determining losses than the speed of release as we had originally theorized.

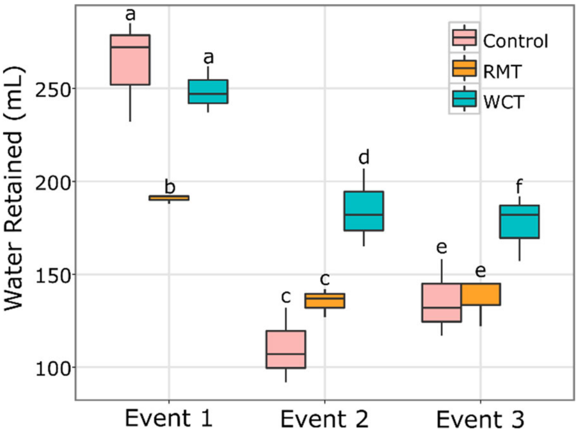

Fig. 4 Water retained (mL) in the soil columns after each of three simulated rain events (535 mL or 66 mm). Soil amendment treatments displayed include control soil represented by the lightest (pink) boxes, soil with incorporated rubber mulch (RMT) represented by the medium shade (orange) boxes, and soil with incorporated coarse woodchips (WCT) represented by the darkest (blue) boxes. A mixed model with fixed effects of treatment and rain event, and random effects of column number, were used to determine significance; letters indicate significance at $p < 0.05$ for treatments after each rain event

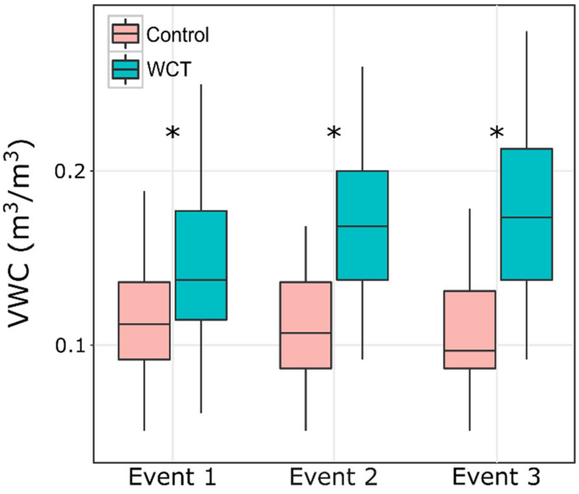

Fig. 5 Volumetric water content (VWC) (m^3/m^3) of fertilized lab columns over three simulated rain events (535 mL or 66 mm). Soil amendment treatments displayed include control columns represented by the lightest (pink) boxes and columns with incorporated coarse woodchips (WCT) represented by the darkest (blue) boxes. A mixed model with fixed effects of soil amendment; rain event, and the day on which the rain event was applied; and random effects of column number and experiment number were used to determine significance, * indicates significance at $p < 0.05$ for each rain event

Although this result seems to run counter to the recommended best management practices in agriculture, which encourage dry incorporation of nutrients (Roberts 2007), it is consistent with our findings of the mechanisms of water retention by incorporated woodchips. Given that the primary method of water retention is absorption, and organic matter retains nutrients through cation exchange capacity, it follows that nutrients in liquid form would have more time and opportunity to be absorbed into the woodchips after application and before a rain event. By comparison, dry granules of fertilizer are more likely to be quickly dissolved, flushed through the column during a rain event, and not interact with the woodchips enough to be absorbed. Observed losses of N were lower than losses of

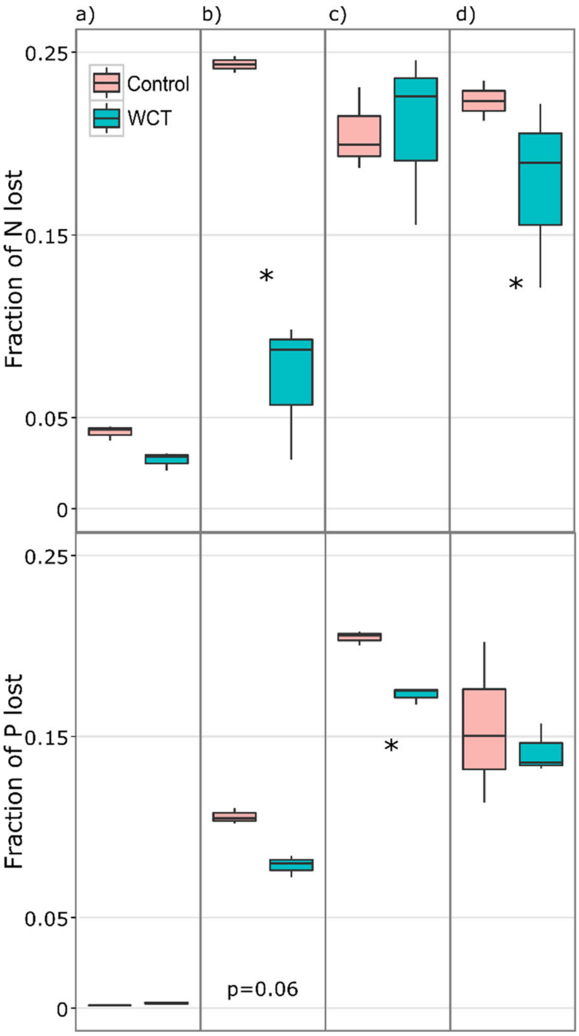

Fig. 6 Fraction of nitrogen (N) and phosphorus (P) demand by grasslands lost from soil columns. Soil amendment treatments displayed include control columns represented by the lightest (pink) boxes and columns with incorporated coarse woodchips (WCT) represented by the darkest (blue) boxes. The vertical panels separate the results by fertilizer treatment: none (a), liquid application (b), incorporated dry application (c), surface applied dry (d). Linear models with fixed effects of soil amendment and fertilizer application method were used to determine significance, * indicates significance at $p < 0.05$ within each fertilizer application method

P; this is consistent with findings by van Es et al. (2006) and van Es et al. (2004), which indicate that sandy soils below P saturation pose less risk to P losses than to N losses. Losses of N and P observed from all columns in this experiment are lower than those observed by other studies examining agricultural soils (Oyarzun et al. 2007).

3.2.3 Gaseous Nutrient Losses from Fertilizers

All GHG fluxes observed in this study were similar to or lower than what is normally observed in cropland (Oertel et al. 2016), with emissions of N_2O and CH_4 being particularly low (Fig. 7). GHG fluxes were evaluated using linear mixed effects models with fixed effects of soil amendment, sampling time, and fertilizer application, and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions for each gas. Significant terms ($p < 0.05$) included both main effects and interaction terms (Fig. 7). We observed significant differences in CO_2 production between control columns and WCT as a main effect (Fig. 7), indicating that the presence of woodchips in the columns is likely increasing microbial respiration. Soil amendment (presence or absence of woodchips) was significant as part of a pair-wise interaction term for N_2O or CH_4 fluxes. Sampling time (pre- vs. post-rain) was significant as part of pair-wise interaction terms for all three gases. In our experiment, rain suppressed CO_2 and CH_4 fluxes and increased N_2O emissions. Although N_2O emissions increased, the decrease in fluxes of CO_2 and CH_4 following a rain event is in contrast to previous work indicating that rain events are hot moments of GHG fluxes (Sponseller 2007). The difficulty in capturing hot moments of GHG fluxes due to their episodic nature is well documented, and it is possible that we simply missed the moment of increased fluxes in our sampling efforts (Groffman et al. 2009; McPhillips et al. 2016; Molodovskaya et al. 2012). Fertilizer application method as a main effect was significant only for CO_2 but was significant as part of pair-wise interactions for all three gases. Fluxes for all GHGs measured were low, less than the median value reported for croplands and grasslands by Oertel et al. (2016), when compared with other studies. We speculate that this is due to a low level of labile C in all soil treatments.

Overall, the results of the mixed effects models indicate that the three variables work together to create differences between the soil columns and result in a nuanced story about the drivers of GHG production in lab soil columns. The authors include two figures in the supplementary materials which provide a more detailed presentation of the gas flux data presented in Fig. 7 (Supplementary Figs. S1. and S3.). Predicted values from the linear mixed effects model are presented with significance letters which support the conclusions from Fig. 7; the three variables presented that soil

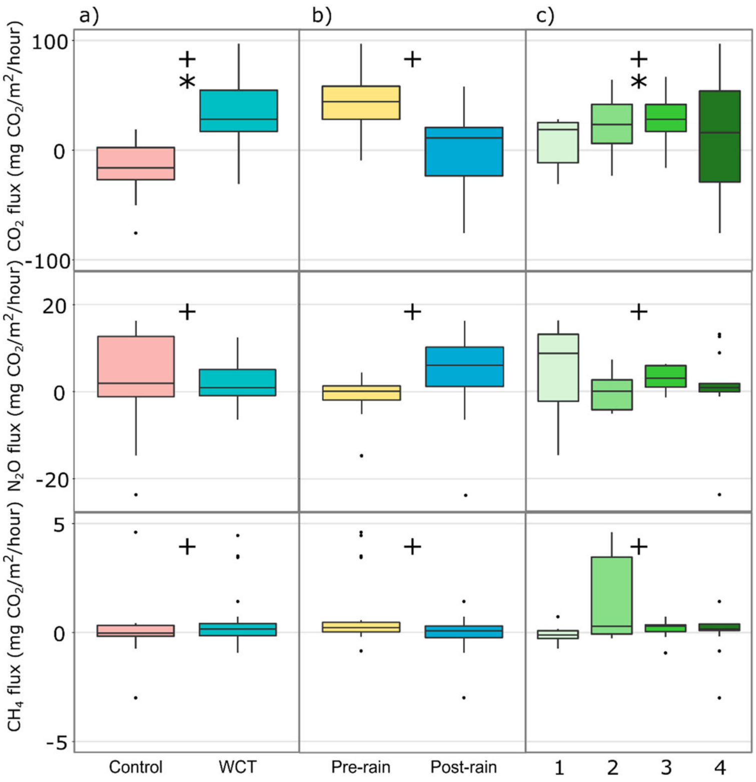

Fig. 7 Carbon dioxide (CO$_2$), nitrous oxide (N$_2$O), and methane (CH$_4$) fluxes presented in CO$_2$ equivalents (mg CO$_2$/m^2/h) from soil columns by soil amendment: control and woodchip treatment (WCT) (a), by wetness pre-rain and post-rain (b), and by fertilizer treatment (c). Fertilizer treatments are none (1), liquid application (2), incorporated dry application (3), surface applied dry (4). Points indicate outliers. Linear mixed effects models with fixed effects of soil amendment, wetness, and fertilizer application and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions for each gas were used to determine significance. * indicates main effect significance and + indicates interaction significance at the $p < 0.05$ level. Refer to Supplementary Fig. S2. to view data presented by analyte rather than in CO$_2$ equivalents

amendment, sampling time, and fertilizer application method work together to drive GHG emissions and that the impact of the predictor variables is not easily separated from one another.

4 Conclusion

This study examined the use of coarse woodchips incorporated into the soil as a restoration strategy for severely degraded sandy soils. We evaluated the ability of incorporated coarse woodchips to retain water and explored some of the mechanisms driving the process. We found that, in the field, incorporated coarse woodchips increase the baseline water content of soils, by capturing rainfall and retaining moisture at higher levels than the control soils. We also observed systematic differences, indicating the ability of incorporated woodchips to increase minimum VWC as well. Similarly, the lab column portion of the study substantiated that woodchips incorporated into the soil increase VWC following simulated rain events and concluded that the primary mechanism of increased water retention is absorption by the woodchips.

We also examined the influence of incorporated woodchips on soluble N and P losses and GHG emissions. We conclude that in a system with incorporated woodchips, fertilizers should be applied in liquid form to maximize retention of both N and P. Gas flux data from this study indicate similar results to other previous studies examining GHG emissions from cropland. From woodchip-amended soils, we saw increased CO$_2$ fluxes, likely indicating an increase in microbial respiration.

There are many opportunities to build on this work and continue examining incorporated coarse woodchips as a soil restoration strategy. The most obvious next step is to examine the behavior of woodchip amendments in the presence of plants over the growing season to examine the availability of retained water and nutrients for biomass production. Similarly, it would be appropriate to examine the role of rain chemistry on the system, either through field trials or the use of synthetic rain water in a laboratory experiment. Lastly, the use of a conservative tracer could be employed to investigate the mechanisms behind retention of N and P by examining the role of adsorption of nutrients to the surface of the woodchips compared with anaerobic processing within woodchips.

The work presented here takes some of the first steps to evaluate coarse woodchips as a viable restoration strategy for sandy soils. As a foundation and a vital provision for reviving sandy and degraded soil, we established the ability of incorporated coarse woodchips to increase initial capture and water holding capacity of sandy soils. While more investigation is necessary before implementation of this technology on a larger scale, we believe the incorporated coarse woodchips to be a viable strategy for restoration of sandy soils degraded through centuries of conversion to agriculture, and other human pressures.

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References

Ajwa, H. A., & Tabatabai, M. A. (1994). Decomposition of different organic materials in soils. *Biology and Fertility of Soils, 18*(3), 175–182. https://doi.org/10.1007/BF00647664.

Barnwell, T., Jackson, R., Elliott, E., Burke, I., Cole, C., Paustian, K., et al. (1992). An approach to assessment of management impacts on agricultural soil carbon. *Water, Air, and Soil Pollution, 64*(1–2), 423–435. https://doi.org/10.1007/BF00477114.

Bouwman, A. F., Van Vuuren, D. P., Derwent, R. G., & Posch, M. (2002). A global analysis of acidification and eutrophication of terrestrial ecosystems. *Water, Air, and Soil Pollution, 141*(1–4), 349–382. https://doi.org/10.1023/A:1021398008726.

Bridges, E. M., & Oldeman, L. R. (1999). Global assessment of human-induced soil degradation. *Arid Soil Research and Rehabilitation, 13*(4), 319–325. https://doi.org/10.1080/089030699263212.

Buchanan, J. R., Yoder, D. C., Denton, H. P., & Smoot, J. L. (2002). Wood chips as a soil cover for construction sites with steep slopes. *Applied Engineering in Agriculture, 18*(6). https://doi.org/10.13031/2013.11322.

Bugbee, G. J. (1999). Effects of hardwood sawdust in potting media containing biosolids compost on plant growth, fertilizer needs, and nitrogen leaching. *Communications in Soil Science and Plant Analysis, 30*(5–6), 689–698. https://doi.org/10.1080/00103629909370238.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications, 8*(3), 559 https://doi.org/10.2307/2641247.

D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., & Runyan, C. W. (2013). Global desertification: drivers and feedbacks. *Advances in Water Resources, 51*, 326–344. https://doi.org/10.1016/j.advwatres.2012.01.013.

Dempster, D. N., Jones, D. L., & Murphy, D. V. (2012). Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil. *Soil Research, 50*(3), 216–221. https://doi.org/10.1071/SR11316.

Fang, S., Xie, B., Liu, D., & Liu, J. (2011). Effects of mulching materials on nitrogen mineralization, nitrogen availability and poplar growth on degraded agricultural soil. *New Forests, 41*(2), 147–162. https://doi.org/10.1007/s11056-010-9217-9.

Ferrini, F., Fini, A., Frangi, P., & Amoroso, G. (2008). Mulching of ornamental trees: effects on growth and physiology. *Arboriculture & Urban Forestry, 34*(3), 157.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., et al. (2005). Global consequences of land use. *Science; Washington, 309*(5734), 570–574.

Fueki, N., Lipiec, J., Kuś, J., Kotowska, U., & Nosalewicz, A. (2012). Difference in infiltration and macropore between organic and conventional soil management. *Soil Science and Plant Nutrition, 58*(1), 65–69. https://doi.org/10.1080/00380768.2011.644759.

Gardner, W. C., Broersma, K., Naeth, A., Chanasyk, D., & Jobson, A. (2010). Influence of biosolids and fertilizer amendments on physical, chemical and microbiological properties of copper mine tailings. *Canadian Journal of Soil Science, 90*(4), 571–583. https://doi.org/10.4141/cjss09067.

Ghane, E., Fausey, N. R., & Brown, L. C. (2014). Non-Darcy flow of water through woodchip media. *Journal of Hydrology, 519*, 3400–3409. https://doi.org/10.1016/j.jhydrol.2014.09.065.

Ghane, E., Feyereisen, G. W., & Rosen, C. J. (2016). Non-linear hydraulic properties of woodchips necessary to design denitrification beds. *Journal of Hydrology, 542*, 463–473. https://doi.org/10.1016/j.jhydrol.2016.09.021.

Głąb, T., & Kulig, B. (2008). Effect of mulch and tillage system on soil porosity under wheat (Triticum aestivum). *Soil and Tillage Research, 99*(2), 169–178. https://doi.org/10.1016/j.still.2008.02.004.

Groffman, P. M., Butterbach-Bahl, K., Fulweiler, R. W., Gold, A. J., Morse, J. L., Stander, E. K., et al. (2009). Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models. *Biogeochemistry, 93*(1), 49–77. https://doi.org/10.1007/s10533-008-9277-5.

Heinonen, J. K., & Lahti, R. J. (1981). A new and convenient colorimetric determination of inorganic orthophosphate and its application to the assay of inorganic pyrophosphatase. *Analytical Biochemistry, 113*(2), 313–317. https://doi.org/10.1016/0003-2697(81)90082-8.

Hudson, B. D. (1994). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation, 49*(2), 189–194.

Kasongo, R. K., Verdoodt, A., Kanyankagote, P., Baert, G., & Ranst, E. V. (2011). Coffee waste as an alternative fertilizer with soil improving properties for sandy soils in humid tropical environments. *Soil Use and Management, 27*(1), 94–102. https://doi.org/10.1111/j.1475-2743.2010.00315.x.

Khaleel, R., Reddy, K. R., & Overcash, M. R. (1981). Changes in soil physical properties due to organic waste applications: a review 1. *Journal of Environmental Quality, 10*(2), 133. https://doi.org/10.2134/jeq1981.00472425001000020002x.

Khan, A. U.-H., & Jury, W. A. (1990). A laboratory study of the dispersion scale effect in column outflow experiments. *Journal of Contaminant Hydrology, 5*(2), 119–131. https://doi.org/10.1016/0169-7722(90)90001-W.

Kidd, J., Manning, P., Simkin, J., Peacock, S., & Stockdale, E. (2017). Impacts of 120 years of fertilizer addition on a temperate grassland ecosystem. *PLoS One, 12*(3), e0174632. https://doi.org/10.1371/journal.pone.0174632.

Kinney, T. J., Masiello, C. A., Dugan, B., Hockaday, W. C., Dean, M. R., Zygourakis, K., & Barnes, R. T. (2012). Hydrologic properties of biochars produced at different temperatures. *Biomass and Bioenergy, 41*, 34–43. https://doi.org/10.1016/j.biombioe.2012.01.033.

Knighton, J. O., & Walter, M. T. (2016). Critical rainfall statistics for predicting watershed flood responses: rethinking the design storm concept. *Hydrological Processes, 30*(21), 3788–3803. https://doi.org/10.1002/hyp.10888.

Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma, 158*(3), 436–442. https://doi.org/10.1016/j.geoderma.2010.05.012.

Lal, R. (2003). Soil erosion and the global carbon budget. *Environment International, 29*(4), 437–450. https://doi.org/10.1016/S0160-4120(02)00192-7.

Larney, F. J., & Angers, D. A. (2012). The role of organic amendments in soil reclamation: a review. *Canadian Journal of Soil Science, 92*(1), 19–38. https://doi.org/10.4141/cjss2010-064.

Li, Z., Schneider, R. L., Morreale, S. J., Xie, Y., Li, C., & Li, J. (2018). Woody organic amendments for retaining soil water, improving soil properties and enhancing plant growth in desertified soils of Ningxia, China. *Geoderma, 310*, 143–152. https://doi.org/10.1016/j.geoderma.2017.09.009.

Li, Z., Qiu, K., Schneider, R. L., Morreale, S. J., & Xie, Y. (2019a). Comparison of microbial community structures in soils with woody organic amendments and soils with traditional local organic amendments in Ningxia of Northern China. *PeerJ, 7*, e6854. https://doi.org/10.7717/peerj.6854.

Li, Z., Schneider, R. L., Morreale, S. J., Xie, Y., Li, J., Li, C., & Ni, X. (2019b). Using woody organic matter amendments to increase water availability and jump-start soil restoration of desertified grassland soils of Ningxia, China. *Land Degradation & Development*. https://doi.org/10.1002/ldr.3315.

Lyon, T. L., & Buckman, H. O. (1943). The nature and properties of soils. *Soil Science, 56*(3), 242.

McPhillips, L. E., Groffman, P. M., Schneider, R. L., & Walter, M. T. (2016). Nutrient cycling in grassed roadside ditches and lawns in a suburban watershed. *Journal of Environmental Quality, 45*(6), 1901–1909. https://doi.org/10.2134/jeq2016.05.0178.

McSwiney, C. P., & Robertson, G. P. (2005). Nonlinear response of N2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. *Global Change Biology, 11*(10), 1712–1719. https://doi.org/10.1111/j.1365-2486.2005.01040.x.

Meffe, R., de Miguel, Á., Martínez Hernández, V., Lillo, J., & de Bustamante, I. (2016). Soil amendment using poplar woodchips to enhance the treatment of wastewater-originated nutrients. *Journal of Environmental Management, 180*, 517–525. https://doi.org/10.1016/j.jenvman.2016.05.083.

Molodovskaya, M., Singurindy, O., Richards, B. K., Warland, J., Johnson, M. S., & Steenhuis, T. S. (2012). Temporal variability of nitrous oxide from fertilized croplands: hot moment analysis. *Soil Science Society of America Journal, 76*(5), 1728–1740. https://doi.org/10.2136/sssaj2012.0039.

NOAA (2015). National Centers for Environmental Information. Global Historical Climatology Network. Meteorological Station Number USC00325479. Available from: https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily.

NOAA (2017). Atlas 4 Point Precipitation Frequency Estimates: ND. Meteorological Station Number USC00325479. Available from: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nd.

O'Dell J. W. (1993). US EPA Method 353.2, Revision 2.0. http://www.epa.gov/Region6/6lab/methods/353_2.pdf.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils—a review. *Chemie der Erde - Geochemistry, 76*(3), 327–352. https://doi.org/10.1016/j.chemer.2016.04.002.

Oyarzun, C., Aracena, C., Rutherford, P., Godoy, R., & Deschrijver, A. (2007). Effects of land use conversion from native forests to exotic plantations on nitrogen and phosphorus retention in catchments of Southern Chile. *Water, Air, and Soil Pollution, 179*(1–4), 341–350. https://doi.org/10.1007/s11270-006-9237-4.

Parfitt, R. L., Giltrap, D. J., & Whitton, J. S. (1995). Contribution of organic matter and clay minerals to the cation exchange capacity of soils. *Communications in Soil Science and Plant Analysis, 26*(9–10), 1343–1355. https://doi.org/10.1080/00103629509369376.

Parkin, T., & Venterea, R. (2010). Chapter 3. GRACEnet trace gas sampling protocols.pdf. In *Sampling Protocols* (pp. 3–1 to 3–39). https://www.ars.usda.gov/ARSUserFiles/np212/Chapter%203.%20GRACEnet%20Trace%20Gas%20Sampling%20Protocols.pdf. Accessed 8 May 2018.

Pelisser, F., Zavarise, N., Longo, T. A., & Bernardin, A. M. (2011). Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition. *Journal of Cleaner Production, 19*(6), 757–763 https://doi.org/10.1016/j.jclepro.2010.11.014.

Peters, A., & Durner, W. (2006). Improved estimation of soil water retention characteristics from hydrostatic column experiments. *Water Resources Research, 42*(11). https://doi.org/10.1029/2006WR004952.

Pluer, W. T., Geohring, L. D., Steenhuis, T. S., & Walter, M. T. (2016). Controls influencing the treatment of excess agricultural nitrate with denitrifying bioreactors. *Journal of Environmental Quality, 45*(3), 772–778. https://doi.org/10.2134/jeq2015.06.0271.

Prats, S. A., MacDonald, L. H., Monteiro, M., Ferreira, A. J. D., Coelho, C. O. A., & Keizer, J. J. (2012). Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. *Geoderma, 191*, 115–124. https://doi.org/10.1016/j.geoderma.2012.02.009.

Reicosky, D. C., Dugas, W. A., & Torbert, H. A. (1997). Tillage-induced soil carbon dioxide loss from different cropping systems. *Soil and Tillage Research, 41*(1), 105–118. https://doi.org/10.1016/S0167-1987(96)01080-X.

Roberts, T. L. (2007). Right product, right rate, right time and right place... the foundation of best management practices for fertilizer. In *Fertilizer Best Management Practices* (pp. 29–32). International Fertilizer Industry Association. http://www.flipbooksoft.com/upload/books/10-2011/d04ebdcf58f732b3a57e168a032fa516/2007_ifa_fbmp_workshop_brussels.pdf#page=36. Accessed 8 May 2018.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 363*(1492), 789–813. https://doi.org/10.1098/rstb.2007.2184.

Sponseller, R. A. (2007). Precipitation pulses and soil CO2 flux in a Sonoran Desert ecosystem. *Global Change Biology, 13*(2), 426–436. https://doi.org/10.1111/j.1365-2486.2006.01307.x.

Truhlar, A. M., Rahm, B. G., Brooks, R. A., Nadeau, S. A., Makarsky, E. T., & Walter, M. T. (2016). Greenhouse gas emissions from septic systems in New York State. *Journal of Environmental Quality, 45*(4), 1153–1160. https://doi.org/10.2134/jeq2015.09.0478.

Van Es, H. M., Schindelbeck, R. R., & Jokela, W. E. (2004). Effect of manure application timing, crop, and soil type on phosphorus leaching. *Journal of Environmental Quality, 33*(3), 1070–1080.

van Es, H. M., Sogbedji, J. M., & Schindelbeck, R. R. (2006). Effect of manure application timing, crop, and soil type on nitrate leaching. *Journal of Environmental Quality, 35*(2), 670. https://doi.org/10.2134/jeq2005.0143.

Zwingmann, N., Singh, B., Mackinnon, I. D. R., & Gilkes, R. J. (2009). Zeolite from alkali modified kaolin increases NH4+ retention by sandy soil: column experiments. *Applied Clay Science, 46*(1), 7–12. https://doi.org/10.1016/j.clay.2009.06.012.