OSMRE National Technology Transfer Team (NTTT), **Applied Science Final Report***

U.S. Department of the Interior, OFFICE OF SURFACE MINING RECLAMATION AND ENFORCEMENT

Miscanthus Production on Mine Soil and its Impacts on Soil Water Balances and Transport of Potential Water Pollutants in Ohio

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Project Description and Objectives:

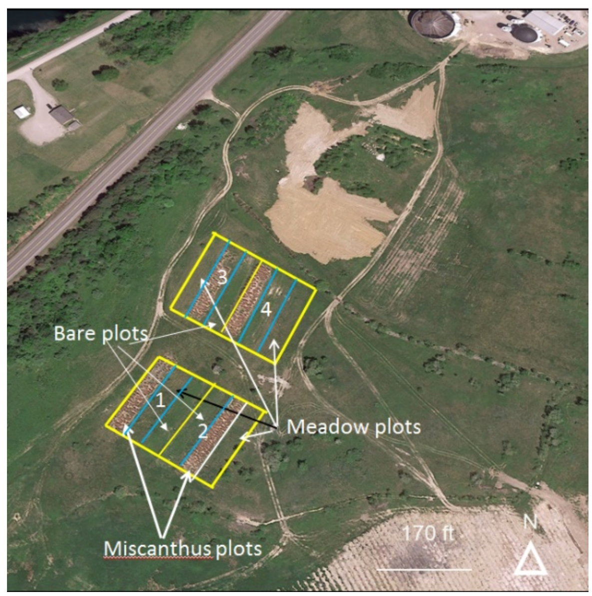
Surface mining for coal and other minerals has created over 1 million hectares (~2.5 million acres) of degraded land in the Appalachian region. Growing biomass feedstock for biofuel on this degraded land can contribute to a more sustainable energy mix. This project assessed the performance of the deep-rooted grass miscanthus (*Miscanthus* × *giganteus*) and its initial environmental effects at a reclaimed mine site converted after almost three decades under meadow land-use near Zanesville, Ohio.

Applicability to Mining and Reclamation:

The results of this 2-year study show that miscanthus can be successfully established on reclaimed mine land accompanied by an improvement in top soil health. Soil compaction should be avoided during site establishment, tillage disturbance should be kept to a minimum, and the soil surface should never be left bare and un-vegetated to reduce leachable nutrient and soil losses. The long-term environmental effects of miscanthus production should, however, also be monitored in subsequent years.

Methodology:

Miscanthus production and its environmental impacts was assessed over 2 years on plots converted after 30-years under meadow land-use. In comparison, plots under meadow with cool-season grasses and legume species, and bare ground control plots were also studied. In addition, the effects of applying liquid effluent from a nearby quasar anaerobic digester were also studied. Gerlach trough for runoff and soil erosion monitoring, and lysimeters for leachate sampling were installed at some plots. Plots were also equipped with soil moisture and temperature sensors. Aboveground and root biomass was determined. Measurements of soil chemical properties included soil organic carbon (SOC) and total nitrogen (TN) concentrations. Soil bulk density, water stable aggregation (WSA) and mean weight diameter (MWD) of aggregates were among measured soil physical properties. Determination of soil hydrological properties included soil water retention curves (SWRC), plant-available water capacity (P-AWC), and runoff volume including nitrate and orthophosphate concentrations.



Aerial view of the study site (Image credit: NOAA, © 2008 Google, Image Landsat/Copernicus; Jose Guzman)

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Highlights:

Important conclusions of the study include the following:

1. Growing miscanthus on reclaimed mine land in Ohio is a viable strategy to produce biomass for bioenergy.

2. Miscanthus improves soil health in the reclaimed mine soil profile due to its high productivity adding high amounts of organic matter to the soil.

3. Applying anaerobic digestate to miscanthus has the advantage of enhancing recycling of nitrogen (N) and phosphorus (P) between miscanthus biomass and effluent production in the anaerobic digester.

Results and Findings:

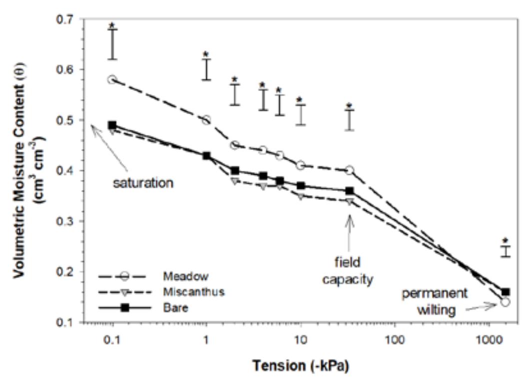
A few of the findings from the study include the following:

- The aboveground biomass yield of miscanthus was four-times and the root biomass yield three-times higher than that of meadow.
- Soil bulk density and MWD of soil aggregates did improve with time under miscanthus land-use which improves soil structure and reduces the risk of soil loss by erosion.
- Applying anaerobic digestate effluent contributed to an increase in topsoil SOC concentrations.
- Disturbance by vehicular traffic and tillage contributed to less favorable hydrological properties under miscanthus compared to that under long-term meadow land-use.

In summary, miscanthus was successfully established on a reclaimed mine soil. While miscanthus had a high biomass production potential, longer monitoring periods are needed to assess how miscanthus productivity changes over time. Similarly, determination of soil properties in subsequent years is needed to assess the effects of growing miscanthus on soil health. Applying effluent from an anaerobic digester is recommended to improve soil health properties but the effects on N and P release and on greenhouse gas (GHG) emissions must also be carefully monitored in the long-term to reduce detrimental environmental effects following effluent application to miscanthus land use.

Anaerobic digestate effluent application during seedbed preparation (Photo credit: Jose Guzman)

Miscanthus growing on the reclaimed mine soil (Photo credit: Jose Guzman)



Soil water retention curves

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Final Report

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Disclaimer

Abstract

Growing biomass as biofuel feedstock on reclaimed mine soils will reduce the competition with growing biomass for food on prime agricultural land. This project studied the initial effects of growing the deep-rooted grass miscanthus (*Miscanthus* × *giganteus*) as biofuel feedstock at a reclaimed mine site converted after almost three decades under meadow land-use near Zanesville, Ohio. Above- and belowground miscanthus biomass production was on average higher than that for meadow, and exploration of the soil profile by deep miscanthus roots will likely improve the health of the reclaimed mine soil. However, initial effects on improvements in soil chemical and physical properties in 0-20 cm (0-8 in) depth were inconclusive as a longer monitoring period is needed. Addition of effluent from a nearby anaerobic digester showed some benefits for soil organic carbon (SOC). However, nitrate and orthophosphate losses to aquatic ecosystems and soil greenhouse gas (GHG) emissions may also increase following effluent addition. Thus, risks and benefits of growing miscanthus on reclaimed mine soils without and with effluent addition should be monitored over a longer study period to support the assessment of miscanthus biomass production on reclaimed mine soil.

Graphical Materials List

Figures

Photos

Introduction

By 2022, gasoline and diesel refineries in the United States are required to process annually at least 80 GL (21 billion gal) of bio-ethanol from non-grain sources under the Energy Independence and Security Act of 2007 (USC 2007). The aim of the act is to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas (GHG) capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes. However, bioenergy feedstocks such as stover residues from corn (*Zea mays* L.) production alone are not able to meet this demand without jeopardizing food security and degrading soil health (Blanco-Canqui 2010). Alternatively, second generation biofuels derived from cellulosic plants may be used but their potential contribution to meet the demand while safeguarding the environment is also unclear (Davis et al. 2009). Competition of biofuel with food production for limited land and water resources can be eased by (i) using prime agricultural lands for food, feed and fiber production, and (ii) growing bioenergy crops with low inputs and water demands on marginal lands and their degraded soils (Qin et al. 2012). Among biofuel crops, perennial C4 grasses such as miscanthus (*Miscanthus* × *giganteus*) and switchgrass (*Panicum virgatum* L.) have a much larger carbon dioxide (CO_2) sink potential and lower GHG emissions when compared with annual biofuel crops such as corn and C3 grass systems (Qin et al. 2015).

In the Appalachian region, degraded reclaimed mine land soils that are potentially suitable for growing bioenergy crops cover more than 1 million hectares (Mha) (~2.5 million ac) following surface mining for coal (Guzman & Lal 2014). Amending these soils with organic matter (OM) has been shown to improve soil health (Haering et al. 2000), but how bioenergy feedstock production on amended reclaimed mine soils responds is uncertain. This study assessed (i) the impact of reclaimed mine soils under meadow which were then converted into miscanthus production on soil physical properties, and temporal changes in SOC and N pools; (ii) the effectiveness of previous mine soil reclamation and post reclamation practices on surface and subsurface water hydrology, soil hydrological properties, and soil quality; (iii) the relationship between surface and subsurface hydrological characteristics with root growth, soil properties, and SOC changes in reclaimed mine soils; and (iv) potential water pollutants such as leaching and surface water runoff of nitrogen (N) and phosphorus (P) from effluent applications losses of soil. The effects of adding nutrients and OM with effluent from an anaerobic methane digester on biomass yield, soil and hydrological properties, and on soil and N and P losses were also studied.

The experiment was implemented on plots established for a previous study. It is important to describe design and history of the study site, treatments of the plots, and summarize major findings for interpretation of the results from the subsequent study.

Executive Summary

Biofuels produced from biomass feedstocks can contribute to a more sustainable energy mix. However, the reduction of the competition with growing biomass for food on limited prime agricultural land necessitates bioenergy feedstock production also on reclaimed mine and other degraded soils. This project assessed the performance of the deep-rooted grass miscanthus (*Miscanthus* × *giganteus*) and its initial environmental effects at a reclaimed mine site converted after almost three decades under meadow land-use near Zanesville, Ohio. The effects of applying liquid effluent from a nearby quasar anaerobic digester were also studied. Miscanthus aboveground biomass production was on average about four-times, and belowground biomass production about three-times higher than that of meadow. The exploration of the soil profile by deep miscanthus roots is expected to improve soil health in the future. However, while soil bulk density and mean weight diameter (MWD) of aggregates in top soil improved with time under miscanthus, both soil physical properties were similar to those for meadow land use at the end of the study. Similarly, the soil organic carbon (SOC) and total nitrogen (TN) concentrations under miscanthus were not higher than those under meadow land use despite higher miscanthus biomass production. Thus, longer monitoring periods are needed to assess whether increased miscanthus biomass inputs translates also into improvements in soil health properties relative to the meadow land use replaced. Otherwise, additions of anaerobic digester effluent resulted in increases in SOC and TN concentrations independent of land use. However, nitrate and orthophosphate losses to aquatic ecosystems also increased after effluent additions. Similarly, carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from the miscanthus soil may also increase following effluent addition based on observations in the previous study. Thus, careful monitoring and probably adjusting of effluent application rates in subsequent years is needed to reduce the risk of increased CO_2 and N_2O emissions, and nitrogen (N) and phosphorus (P) release into the environment, and to enhance N and P recycling between miscanthus biomass and effluent production in the anaerobic digester. In summary, miscanthus was successfully established on a reclaimed mine soil. While miscanthus had a high biomass production potential, longer monitoring periods are needed to assess how miscanthus productivity changes over time. Similarly, determination of soil properties in subsequent years is needed to assess the effects of growing miscanthus on soil health. Applying effluent from an anaerobic digester is recommended to improve soil health properties but the effects on N and P release and on greenhouse gas

(GHG) emissions must also be carefully monitored in the long-term to reduce detrimental environmental effects following effluent application to miscanthus land use.

Experimental

Site description

The site was located near Zanesville in Muskingum County, Ohio (39°51′22.82″ N, 82°06′57.61″ W) (Fig. 1). This area was mined for coal and lime until 1986, and reclaimed following standard surface mining sites reclamation techniques (Guzman et al. 2017). These include backfilling mine pit with spoil, grading to approximately original contour, and spreading stored topsoil over the graded land surface. After topsoil addition, the reclaimed mine soil was seeded with a mixture of cool-season grasses and legume species. Records of seedling mixtures, seed rates and soil amendments applied during the reclamation process in 1986 were not available. In 1989, the most abundant grass species was Kentucky 31 tall fescue (*Festuca arundinacea* Schreb.), and the most abundant legume was bird's-foot trefoil (*Lotus corniculatus* L.). The pre-mining soil at the site was classified as Morristown (loamy-skeletal, mixed, active, calcareous, mesic Typic Udorthents; Guzman et al. 2017).

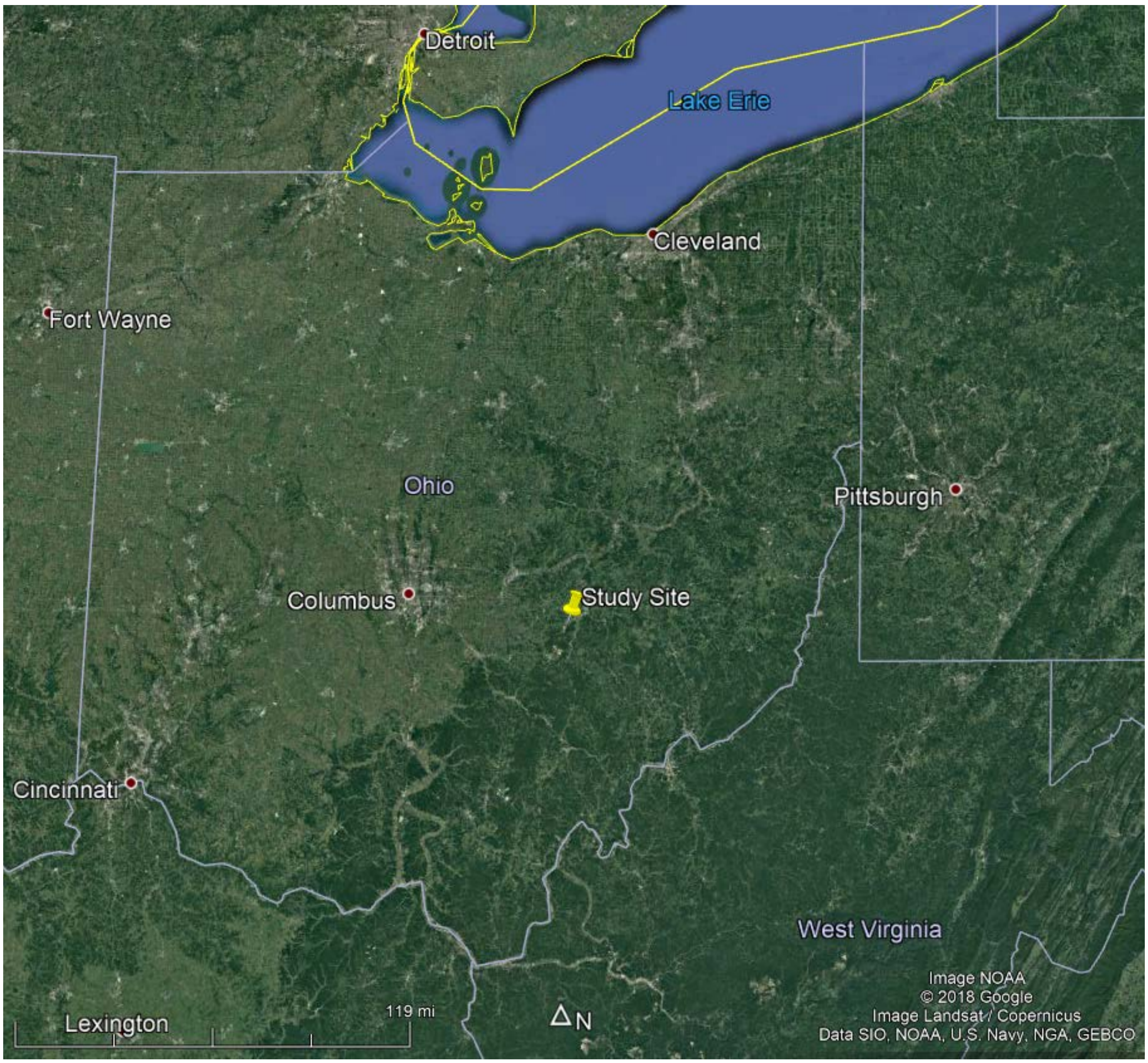

Figure 1. Location of the study site in Ohio (Image credit: NOAA, © 2008 Google, Image Landsat/Copernicus)

In 2013, the topsoil depth at the reclaimed experimental site ranged from 10 to 30 cm (4 to 12 in) depth (Guzman et al. 2019). The newly formed topsoil or A horizon in 10 to 20 cm (4 to 8 in) depth was a silty clay loam, consisting of 10 to 28% sand, 15 to 35% clay, 17 to 23% by volume of gravel, and a pH ranging from 7.1 to 7.7. The soil organic carbon (SOC) and total nitrogen (TN) concentrations were on average 2.13 % C and 0.18 % N, respectively. The depth of the underlying C horizon formed from the backfilled overburden material ranged from 20 to >40 cm (8 to >16 in), and texture was silty clay loam, consisting of 15 to 33% sand, 10 to 35% clay, 35 to 45% by volume of gravel, and pH ranging from 7.5 to 8.6. The SOC and TN concentrations of the C horizon were on average 0.66 % C and 0.06 % N, respectively. Long-term mean annual precipitation for the study site was 960 mm (38 in), mostly occurring during the growing season between May and September. The mean annual temperature was 11 °C (52 °F), and the number of frost-free days ranged from 160 to 180 (Guzman et al. 2019).

Design of previous study

The study site was originally established in spring 2013 for a previous project funded by the USDA NIFA Biomass Research Development Initiative (*Award No. 2012-1008-2032, 2012 to 2015*) with three land uses replicated four times, and a total of 72 plots (Fig. 2). Plot dimensions were 9 x 9 m (30 x 30 ft).

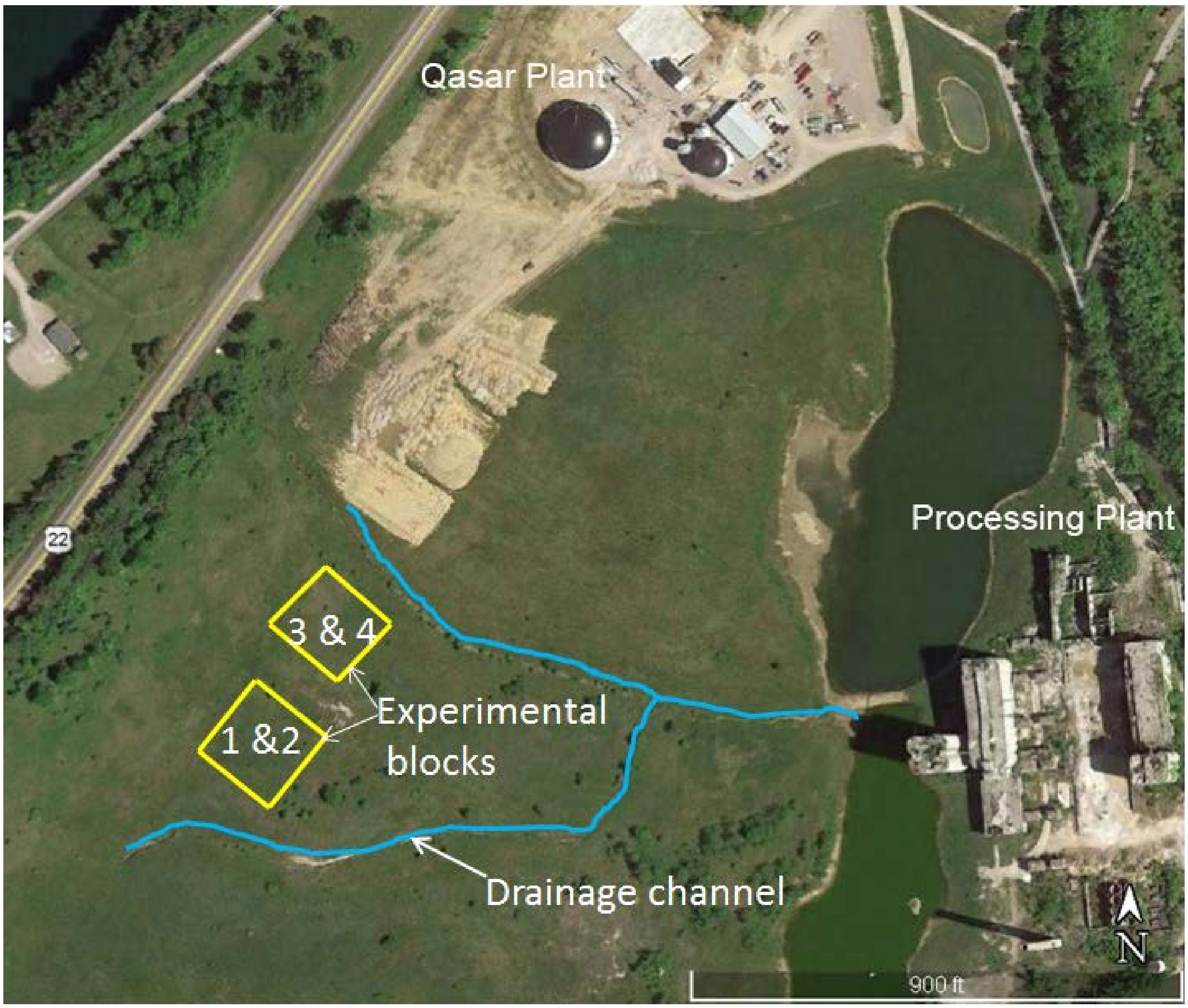

Figure 2. Aerial view of the location of the experimental blocks of the previous study in May 2013 (Quasar anaerobic digestion plant located to the North, coal and limestone processing plant located to the East; Image credit: NOAA, © 2008 Google, Image Landsat/Copernicus; Jose Guzman)

Photo 1. Reclaimed mine site under meadow after snow melt in 2013 (Photo credit: Jose Guzman).

The reclaimed mine soil was originally under meadow (Photo 1). The main plots were land use, i.e., meadow (27 yrs old in 2013), miscanthus and corn (Fig. 3). Soil at the meadow plots was kept relatively undisturbed. However, land-use conversion from meadow to miscanthus or corn involved repeated soil disturbance by disk plowing up to 20 cm (8 in) depth for seedbed preparation (Photo 2).

Photo 2. Seedbed preparation for miscanthus and corn establishment (Photo credit: Jose Guzman).

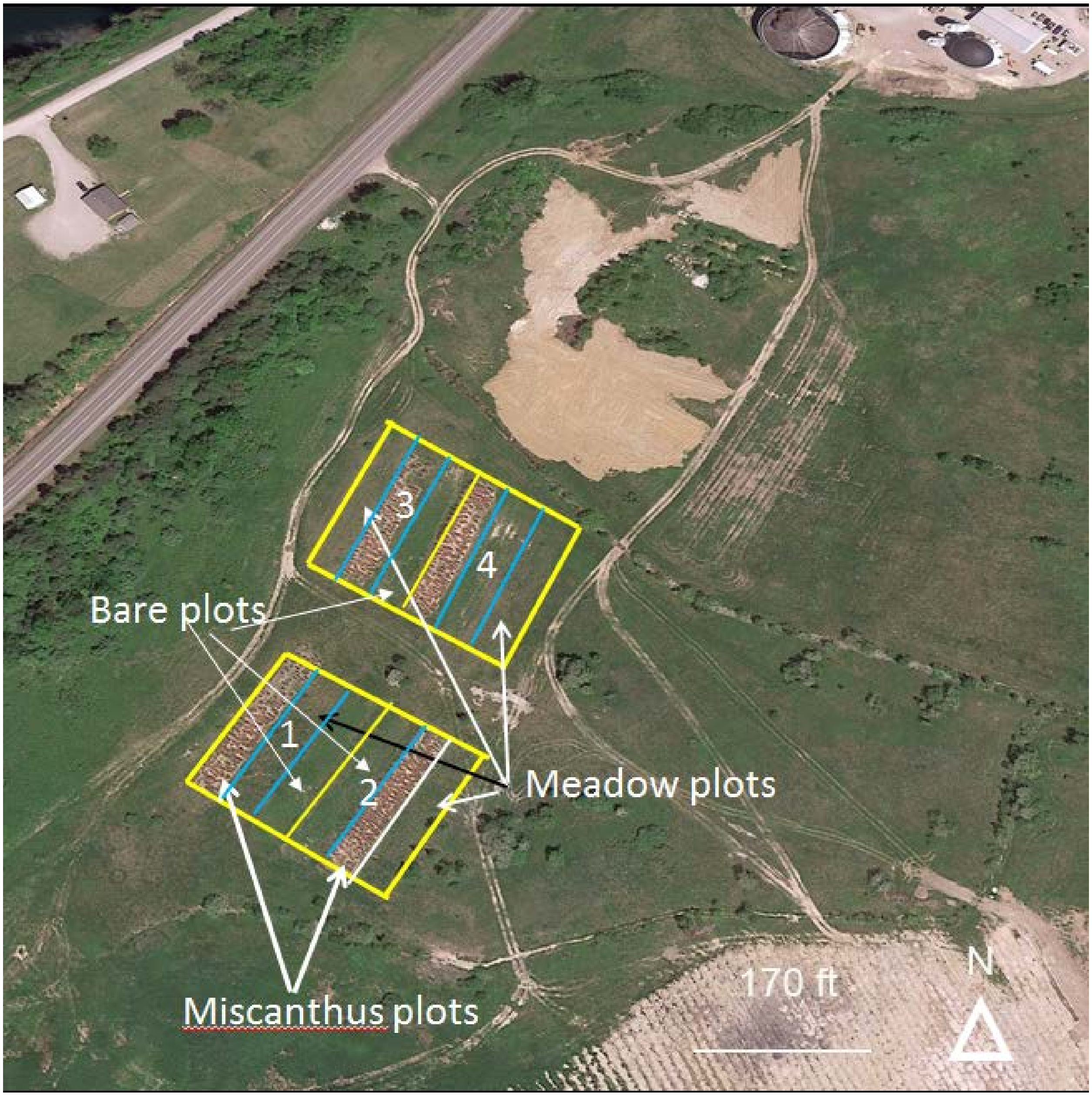

Figure 3. Aerial view of the current study in March 2017 {numbers inside the yellow boxes represent experimental blocks; blue lines separate main plots – meadow, miscanthus and bare soil (under corn in the previous study) land uses} (Image credit: NOAA, © 2008 Google, Image Landsat/Copernicus; Jose Guzman).

Subsequently, soil at the miscanthus plots was maintained without tillage disturbance. However, soil at the corn plots was disturbed by tillage every spring at the beginning of the growing season in 2014 and 2015. At each land use, the main plots were split into five plots. One plot was not fertilized and served as control. Two miscanthus and two meadow plots received N application rates of 75 kg N ha^{-1} (70 lb N per ac), and two received 150 kg N ha^{-1} (134 lb N per ac). Either inorganic fertilizer or liquid effluent (<15% biosolids) from a nearby quasar anaerobic digester was added to two plots (Photos 3 and 4). The digester produces methane (CH_4) from sewage sludge and food waste. In the corn plots, higher rates of 150 kg N ha^{-1} (134 lb N per ac) and 225 kg N ha^{-1} (201 lb N per ac) as inorganic fertilizer or effluent were applied (Fig. 4a). Corn planting was discontinued and plots left bare after three consecutive growing seasons at the end of the USADA-NIFA project in 2015.

Photo 3. Tractor-pulled tanker applying effluent in 2013 (Photo credit: Jose Guzman).

Photo 4. Tilled soil surface after effluent application (Photo credit: Jose Guzman).

Results of the previous study

Aboveground dry biomass yield of corn, miscanthus and meadow in 2013-2015 is shown in Table 1. Miscanthus aboveground dry biomass yield increased as the years progressed mainly due to rhizomes expansion and maturity that resulted in increased numbers of tillers (Ussiri et al. 2019). However, N fertilization had no effect on yield during the initial 3 years probably due to high soil N contents as the site was under reclaimed meadow including N-fixing legumes for 27 years. Miscanthus yield may respond to N addition in subsequent years as soil N may be increasingly mobilized and removed by bioenergy feedstock harvest. However, it is expected that miscanthus will maintain high yields in the long-term (Ussiri et al. 2019).

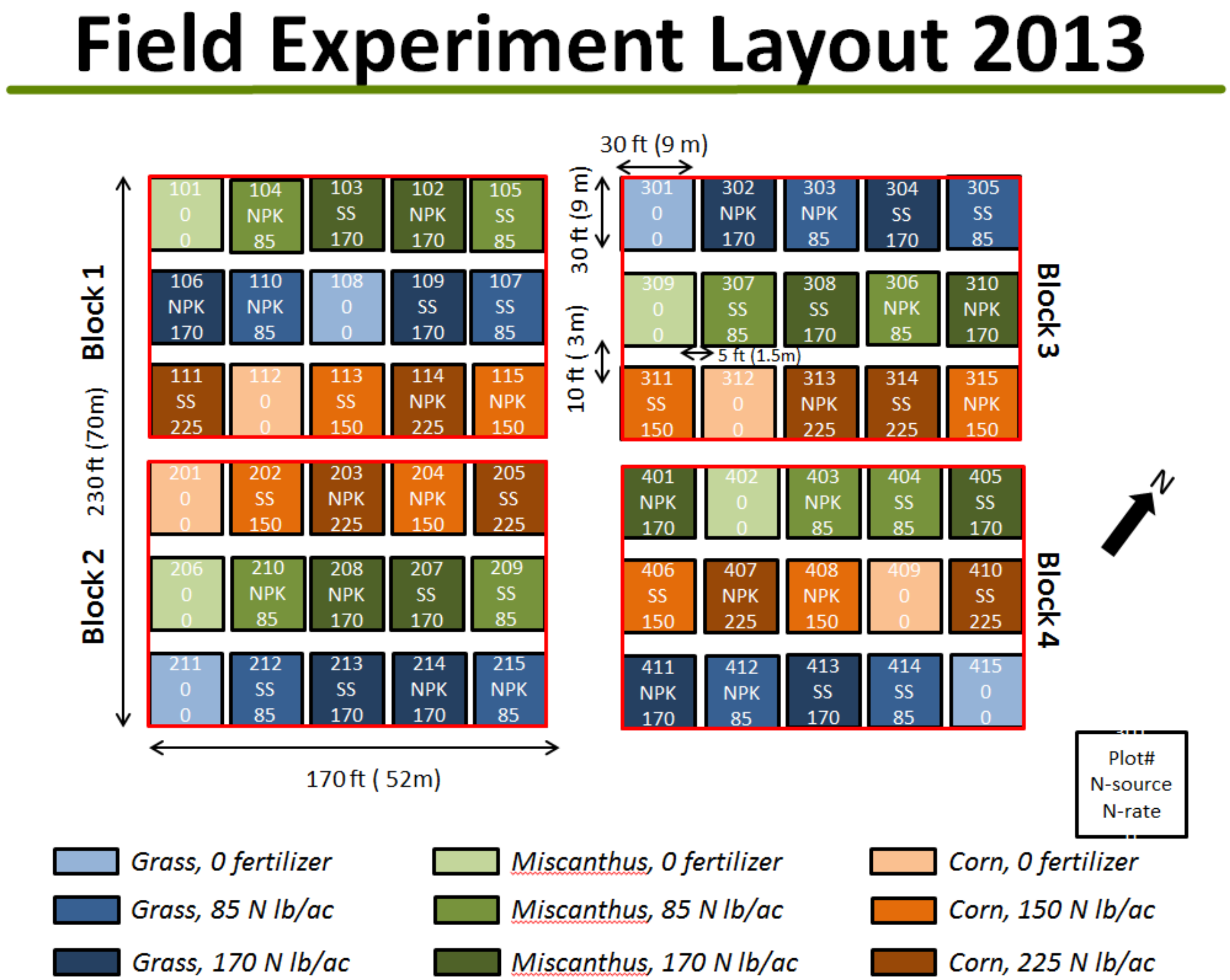

Figure 4a. Previous field experiment layout showing semisolid (SS) anaerobic effluent-N and inorganic fertilizer (NPK)-N application rates for each plot during the 2013 to 2015 growing seasons.

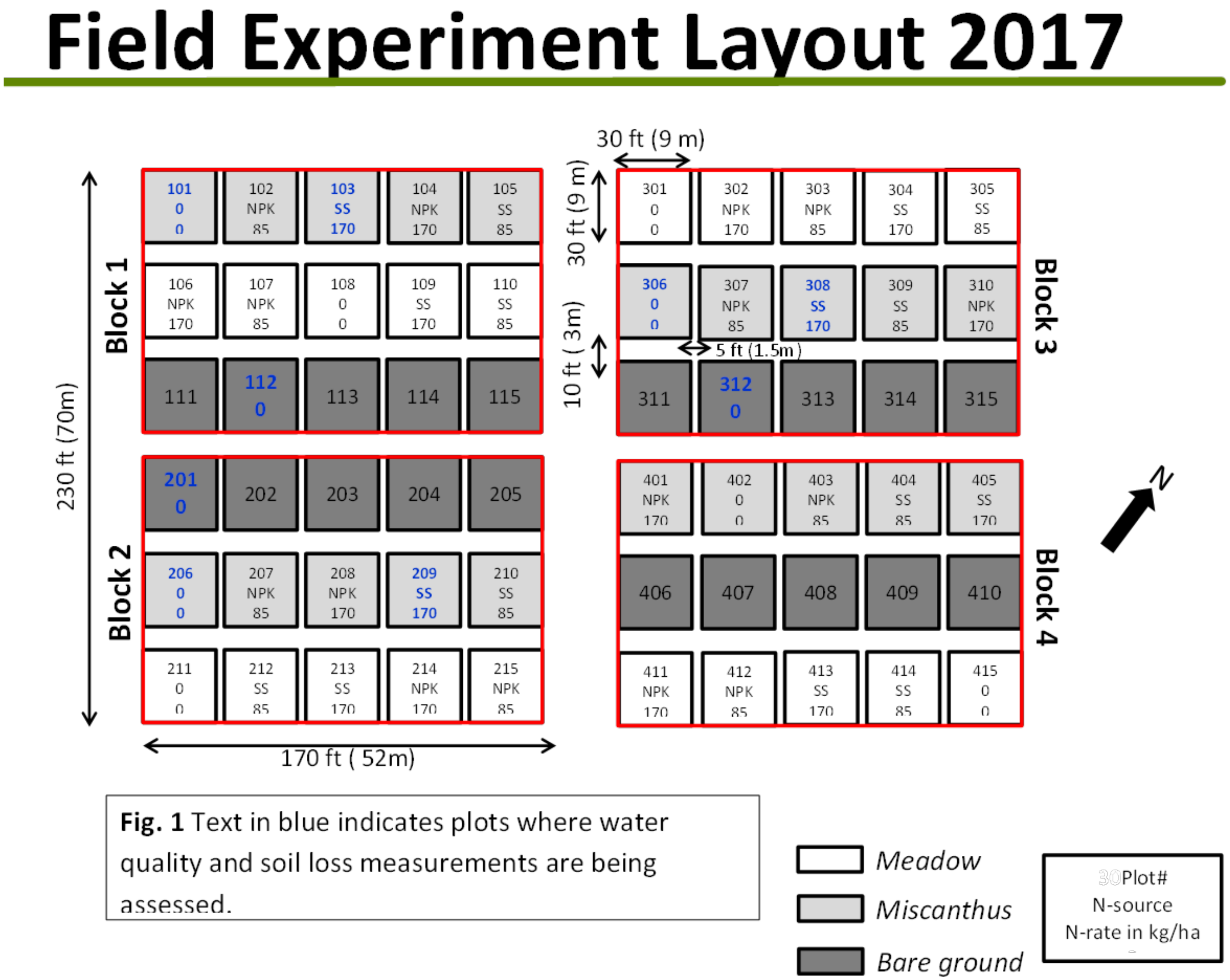

Figure 4b. Current experimental layout with semisolid (SS) anaerobic effluent-N and inorganic fertilizer (NPK)-N application rates highlighting plots with runoff and erosion monitoring.

Table 1. Aboveground dry biomass yield (Mg ha^{-1}) for meadow, corn and miscanthus in 2013-2015 for the previous study (Numbers in brackets are standard deviations).

Land use	2013	2014	2015
Meadow	8.90 (0.76)	6.54 (0.83)	8.65 (1.98)
Miscanthus	2.01 (0.17)	7.16 (1.98)	19.64 (8.62)
Corn	2.31 (1.06)	14.38 (1.13)	8.42 (2.32)

(tons per acre)

Land use	2013	2014	2015
Meadow	3.97 (0.34)	2.92 (0.37)	3.86 (0.88)
Miscanthus	0.90 (0.08)	3.19 (0.88)	8.76 (3.85)
Corn	1.03 (0.47)	6.41 (0.50)	3.76 (1.03)

The SOC and N concentrations in 0-20 cm (0-8 in) depth in 2013 and 2015 were not different between the plots (Data not shown). This can be explained by the slow response of soil organic matter (SOM) to changes in vegetation cover and soil management after being previously 27 years under meadow land use. Steady-state conditions in SOC and TN concentrations and stocks are only reached after consistent management practices have been applied over several decades. Specifically, SOC and TN change slowly in temperate climates as was shown, for example, by observations of SOM dynamics in 0-25 cm (0-10 in) soil depth over 70 years at crop rotations in England (Johnston et al. 2017). However, reductions in soil microbial biomass C and increases in carbon dioxide (CO_2) emissions at the corn and miscanthus plots indicated that tillage disturbance may have caused small although insignificant losses in SOC. Apparently, effluent C retained in the soil did offset some of these small SOC losses (Guzman et al. 2017). Some sensitive soil physical properties responded to the disturbance associated with land use change from meadow to miscanthus and corn. For example, soil bulk density in 0-10 cm (0-4 in) depth increased by 9% under miscanthus and corn relative to that of meadow (Guzman et al. 2019). Soil aggregation, water infiltration and plant-available water capacity all decreased after land-use change from meadow to miscanthus or corn. In contrast, GHG emissions were higher for miscanthus and corn land-uses than those under meadow (Guzman et al. 2017).
In summary, converting from reclaimed meadow to miscanthus and corn land-uses negatively affected soil health properties initially, and resulted in a net increase in soil GHG emissions which was also promoted by effluent additions. However, whether these negative effects continue into the future needs long-term monitoring.

Introduction and objectives current study

The subsequent project was implemented on some of the previously studied plots and land uses shown in Figs. 3 and 4a. The field experiment layout of the current study is shown in Fig. 4b. Among the aims were to assess the impacts of reclaimed meadow and miscanthus land uses, with or without effluent amendment, on water quality as well as on soil physical, chemical and hydrological properties, and on biomass production. The overall goal was to assess the potential of post-reclamation management practices to improve hydrology and water quality. Another goal was to assess associated changes in terrestrial (both soil and vegetation) carbon (C) pools in reclaimed mine lands, the potential for offsetting CO_2 emissions, and the potential enhancement in biomass production for bioenergy production which would increase the economic value of the reclaimed mined lands.
The project had the following specific objectives:

1. Monitor the impact of reclaimed mine soils under meadow which were then converted into miscanthus production on soil physical properties, and temporal changes in SOC and N pools.
2. Evaluate the effectiveness of previous mine soil reclamation and post reclamation practices on surface and subsurface water hydrology, soil hydrological properties, and soil quality.
3. Establish relationship between surface and subsurface hydrological characteristics with root growth, soil properties, and SOC changes in reclaimed mine soils.
4. Measure and budget potential water pollutants such as leaching and surface water runoff of N and P from effluent applications.

Table 2. Overview over soil parameters measured at each plot.

Plot #	Land use	Soil chemical properties	Soil physical properties	Soil hydrological properties
101	Miscanthus	TC, IC, coal C; TN	Soil moisture and temperature; bulk density; MWD; WSA	Runoff volume and NO_3^- and PO_4^{3-} concentrations; soil loss; leachate; infiltration; SWRC; P-AWC
103	Miscanthus	TC, IC, coal C; TN	Soil moisture and temperature; bulk density; MWD; WSA	Runoff volume and NO_3^- and PO_4^{3-} concentrations; soil loss; leachate; infiltration; SWRC; P-AWC
112	Bare ground	TC, IC, coal C; TN	Soil moisture and temperature; bulk density; MWD; WSA	Runoff volume and NO_3^- and PO_4^{3-} concentrations; soil loss; leachate; infiltration; SWRC; P-AWC
201	Bare ground	TC, IC, coal C; TN	Soil moisture and temperature; bulk density; MWD; WSA	Runoff volume and NO_3^- and PO_4^{3-} concentrations; soil loss; leachate; infiltration; SWRC; P-AWC
206	Miscanthus	TC, IC, coal C; TN	Bulk density; MWD; WSA	Infiltration; SWRC; P-AWC
209	Miscanthus	TC, IC, coal C; TN	Bulk density; MWD; WSA	Infiltration; SWRC; P-AWC
306	Miscanthus	TC, IC, coal C; TN	Bulk density; MWD; WSA	Infiltration; SWRC; P-AWC
308	Miscanthus	TC, IC, coal C; TN	Bulk density; MWD; WSA	Infiltration; SWRC; P-AWC
312	Bare ground	TC, IC, coal C; TN	Soil moisture and temperature; bulk density; MWD; WSA	Runoff volume and NO_3^- and PO_4^{3-} concentrations; soil loss; leachate; infiltration; SWRC; P-AWC

TC Total carbon; IC Inorganic carbon; TN Total nitrogen; MWD Mean weight diameter; WSA Water stable aggregation; SWRC Soil water retention curve; P-AWC Plant-available water capacity

Materials and methods

Experimental design and plot layout

Similar to the previous study, the main plot treatment was vegetation cover, i.e., (i) meadow with cool-season grasses and legume species, and (ii) miscanthus (Fig. 4). However, the former corn plots were maintained as (iii) bare ground control plots. Two miscanthus plots (#101 without and #103 with effluent addition), and one bare ground plot in blocks 1, 2 and 3 (#112, 201, and 312) were installed with Gerlach trough for runoff and soil erosion loss monitoring (Gerlach 1967; Photo 5; Table 2). The slope gradient for each Gerlach trough installed ranged from 2 to 3%, with a collection area of 4050 cm^2 (628 sq. in). The Gerlach trough consisted of a metal box or through with a lip on the upslope side flush with the soil surface to ensure that overland flow and transported sediment are guided into the container. The high walls prevent splashed material from entering the container as only overland flow-transported sediment is monitored. Gerlach troughs indicate relative amounts of erosion during a given period (Gerlach 1967).

Photo 5. Left: Gerlach trough in a miscanthus plot for monitoring surface soil erosion and runoff water quality (Red arrow indicates runoff water collection area, brown arrow indicates location of Gerlach trough, blue arrow indicates where excess runoff is collected connected by a tube); Right: Detailed view of Gerlach trough in a miscanthus plot looking downslope (Photo credit: Jose Guzman).

In each of the two miscanthus plots and the bare ground plot in blocks 1, 2 and 3, one lysimeter was installed at 25 cm (10 in) depth near each Gerlach trough for sampling leachate below the root zone (Photo 6). Soil moisture and temperature sensors were also inserted in 5, 15 and 25 cm (2, 6 and 10 in) depth at the five plots for continuously recording soil moisture and temperature every 30 minutes (Photo 6). Mineral fertilizer and effluent-N application rates at the miscanthus and meadow plots were similar to those of the previous study. Water quality and soil erosion monitoring was not implemented under meadow land use.

Photo 6. Left: Lysimeter in the middle of a miscanthus plot for collecting leachate at a depth of 25 cm (10 in) just below the root zone (Gerlach trough in the background); Right: Data logger (red arrow) in a miscanthus plot connected to soil temperature and moisture sensors inserted at soil depths of 5, 15, and 25 cm (2, 6 and 10 in) depth (Gerlach trough in the middle) (Photo credit: Jose Guzman).

Soil sampling and analyses

Soil samples were collected at 0-10, 10-20, 20-30 and 30-40 cm (0-4, 4-8, 8-12 and 12-16 in) depth intervals using a 1.7 cm (0.7 in) diameter and 60 cm (24 in) long soil core probe at 5-8 locations within each plot. Soil samples were composited per depth and plot, air-dried, and sieved to pass through a 2-mm (0.08 in) sieve. Sub-samples for C and N analysis were ground by mortar and pestle to pass through a 250-µm (0.01 in) sieve. Total C and N concentrations were determined by the dry combustion method (900 °C or 1,652 °F) using a CN elemental analyzer (Thermo Fisher Scientific FLASH 2000 CN Soils, Bremen, Germany)[1]. SOC concentration was obtained after correcting total C for inorganic and coal C concentrations.

For determination of soil bulk density, 7.5 x 7.5 cm (3 x 3 in) cores were retrieved from the plots. Cores were collected at 0-10, 10-20, 20-30, and 30-40 cm (0-4, 4-8, 8-12 and 12-16 in) depth intervals. Soil cores were trimmed at both ends, and bulk density was determined by standard core method (Grossman and Reinsch 2002). To correct for gravel content, bulk density of the fine earth fraction (< 2.0 mm or 0.08 in) was determined by measuring the volume of gravel (> 2.0 mm fraction) using the water displacement method[2]. Soil cores were then oven dried at 105°C (221 °F) for 24 hours and weighed. Soil bulk density (Mg m^{-3}) was calculated as the dried soil mass divided by the core volume. Total porosity at the top 10 cm (4 in) soil depth was determined by measuring soil moisture content at time of saturation using the same soil cores as those collected for soil bulk density (Grossman and Reinsch 2002).

Two soil samples per plot were taken for water stable aggregate (WSA) distribution using a 10.5-cm (4 in) diameter golf course hole cutter inserted at 20-cm (8 in) depth in each plot (between and within rows at the miscanthus plots). Soil samples per plot were then homogenized, and gently passed through an 8-mm sieve to remove any plant residues and rocks. The WSA size distribution was determined following the standard procedure for air-dried samples (Nimmo and Perkins 2002; Yoder 1936). Briefly, 50 g (0.11 lbs) of < 8 mm (0.3 in) fraction was used for wet sieving for 30 min in water at 21°C (70 °F). Aggregate stability was assessed by wet-sieving using a nest of five sieves {4.75, 2, 1, 0.5 and 0.25 mm (0.19, 0.08, 0.04, 0.02 and 0.01 in) sieve openings}. Prior to the wet sieving, all soil samples were first misted with a spray bottle and then submerged in water in the top 4.75-mm (0.19-in) sieve for at least 5 min to slake air dried soil. Wet-sieving was achieved by lowering and then raising the nest of sieves with a stroke length of 30 mm and a frequency of 1 stroke min^{-1} for 30 minutes using a custom made sieving machine. Stable aggregates retained on each sieve were removed from sieves, oven-dried (60°C or 140°F), and weighed for WSA determination and calculation of mean weight diameter (MWD) of aggregates. Seven aggregate size fractions were collected, namely >4.75 mm, 2-4.75 mm, 1-2 mm, 0.5-1 mm, 0.25-0.5 mm, 0.05-0.25 mm and the remaining sample that passed through the last sieve, i.e., <0.053 mm (0.002 in). The aggregate stability for each soil sample was then expressed by MWD as:

$$\mathrm{MWD} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \overline{\mathrm{xi}} \times \mathrm{wi} \quad (1)$$

where, $\bar{x}_i$ is the mean diameter (mm) of the size fractions separated by sieving and w_i is the mass of aggregates in that size range as a fraction of total dry mass of the soil (Nimmo and Perkins 2002; Youker and McGuinness 1957).

Soil hydrological properties measurements

While in Spring 2017 steady state infiltration rates were determined based on the Cornell Sprinkle Infiltrometer system (Van Es and Schindelbeck 2003), the Mini Disk Infiltrometer was used during Fall 2018 to determine steady

[1] Soil samples (~10 mg or 0.0004 ounces) are weighed in tin containers, introduced into a combustion reactor with a proper amount of oxygen, and combusted at 900 °C. The resultant gases are carried by helium flow to a second reactor filled with copper, then through a water trap, a gas-chromatograph column and finally, N_2 and CO_2 concentrations derived from total N and C contents in the soil sample are measured by a Thermal Conductivity Detector.

[2] Gravel fragments (GFs) are thoroughly cleaned to remove attached soil particles and air-dried. Then, each GF is coated with paraffin so that water would not be absorbed through the micropores in the GF. Water is filled into a graduated cylinder and the water volume level recorded. Then, the coated GFs are immersed in the water and the increase in water volume level recorded. The difference between the volume level of the RF in water and the volume level of the water is equal to the GF volume.

state infiltration rates (Decagon Devices, Inc. 2016)[3]. Measurements were done at the bare ground plots #112, 201 and 312; the miscanthus plots #101, 206 and 306; and the miscanthus plots with effluent addition #103, 209 and 308. Soil water retention curves (SWRC) were determined by using a combination of tension table and pressure plate extractors (Dane and Hopmans 2002). The same soil cores that were collected for bulk density were initially used for determination of SWRC. The SWRC tension points were determined by both tension table and pressure plate. Volumetric water content at tension points -0.25 (near saturation), -1, -2, -4, and -6 kPa (-0.04, -0.15, -0.29, -0.58 and -0.87 psi) were determined by tension table, and that at -10, -33, and -1,500 kPa (-1.45, -4.79 and -217.6 psi) with pressure plate extractors. Soil moisture content at each matric potential was determined gravimetrically by loss of moisture weight and converting it to volumetric moisture content (θ, $cm^3\ cm^{-3}$), based on bulk density of the soils (corrected for gravel). Plant available water capacity (P-AWC) was calculated by subtracting the volumetric moisture content at the permanent wilting point (PWP, -1,500 kPa) from that at the field capacity (–33 kPa; Dane and Hopmans 2002).

Results and Discussion

The overall objective was to evaluate the effects of converting temperate cool season grasslands (meadow) established on reclaimed mine soil into miscanthus (*Miscanthus* x *giganteus*) plantation for bioenergy and to demonstrate that reclamation techniques and post-reclamation management practices are effective means for improving hydrology and water quality while also increasing terrestrial C pools in reclaimed mine soils, offsetting CO_2 emissions and enhancing biomass production for bioenergy.

Objective 1: Monitoring the impact of reclaimed mine soils under meadow which were converted into miscanthus production on soil physical properties, and temporal changes in SOC and N pools.

Biomass

Plant biomass- and, particularly, root biomass-C inputs are the major source of SOM (Rasse et al. 2005). The average aboveground biomass for 2017-2018, and root biomass ($Mg\ ha^{-1}$ and $ton\ ac^{-1}$) for 2018 are shown in Table 3 while aboveground biomass per plot is shown in Table C1.

Table 3. Mean aboveground dry biomass yield ($Mg\ ha^{-1}$) for miscanthus and meadow averaged over all plots and study years 2017 and 2018, and average root biomass yield in 2018 (Numbers in brackets are standard deviations)

	Miscanthus	Meadow
Control	29.3 (1.6)	7.6 (0.5)
Fertilized	29.9 (2.3)	7.7 (1.0)
Root biomass	37.8	12.5

[3] The Mini Disk Infiltrometer consists of a tube separated into two chambers, and a sintered steel disc at the bottom. The upper and lower chambers are both filled with water. The top or bubble chamber controls the suction. The lower chamber contains a volume of water that infiltrates into the soil at a rate determined by the suction selected in the bubble chamber. The lower chamber is labeled like a graduated cylinder with volume shown in mL. Once the Infiltrometer bottom is placed on a soil, water begins to leave the lower chamber and infiltrate into the soil at a rate determined by the hydraulic properties of the soil. As the water level drops, the volume at specific time intervals (like every 30 seconds for a silt loam soil) is recorded. Data are plotted using a Microsoft excel spreadsheet.

(tons per acre)

	Miscanthus	Meadow
Control	13.1 (0.7)	3.4 (0.2)
Fertilized	13.3 (1.0)	3.4 (0.4)
Root biomass	16.9	5.6

Miscanthus biomass was about three-times that of meadow. The higher root biomass at the miscanthus plots will likely contribute to higher SOC stocks in the soil profile in the future as miscanthus can develop roots to deeper than 3-m (10 ft) depths (Lewandowski et al. 2003). However, effects of land use on SOC stocks were not assessed as monitoring periods of several decades are needed until a new equilibrium between soil C inputs from plant residues and roots and losses mainly by decomposition is in place after a land use change (Johnston et al. 2017). Nevertheless, changes in SOC and TN concentrations are discussed below.

The aboveground yields of both meadow and miscanthus did not respond to differences in N fertilization types and application rates which was also reported by others (e.g., Kering et al. 2012; Larsen et al. 2014). For meadow, this may be related to high TN concentrations in 0-10 cm (0-4 in) depth due to long-term N inputs by the N-fixing legume bird's-foot trefoil present in the meadow plant community for almost 30 years (Table 6). Otherwise, miscanthus is a low management and high yielding grass species with efficient N recycling by translocating N into belowground rhizomes (Heaton et al. 2009). Thus, miscanthus biomass growth did not respond to N fertilization initially. However, removing miscanthus biomass for bioenergy will also remove N from the site in subsequent years. Whether this N loss needs to be balanced by fertilization requires long-term monitoring (Heaton et al. 2009).

Soil physical properties

Soil physical and hydrological properties for specific sampling dates are included in Appendix A. Table 4 shows the mean values of soil bulk density and MWD in 0-10 cm (0-4 in) depth for 2017 and 2018 allowing an assessment of temporal changes.

Table 4. Mean values for bulk density and mean weight diameter (MWD) in 0-10 cm (0-4 in) depth for meadow, miscanthus and bare soil prior to the 2017 and after the 2018 growing seasons.

	Bulk Density ($g\ cm^{-3}$)		Mean Weight Diameter (mm)	
	2017	2018	2017	2018
Meadow	1.16	1.18	2.00	2.65
Miscanthus	1.28	1.14	0.96	2.63
Bare	1.25	1.29	1.45	2.38

	Bulk Density (lb per cubic ft)		Mean Weight Diameter (in)	
	2017	2018	2017	2018
Meadow	72.4	73.7	0.08	0.10
Miscanthus	79.9	71.2	0.04	0.10
Bare	78.0	80.5	0.06	0.09

Bulk density prior to the growing season in 2017 was higher for miscanthus and bare soil compared to that under meadow land use. However, following the 2018 growing season only bare soil had a higher bulk density. The higher bulk density at the former corn and now bare plots may result from the absence of soil loosening by (i) tillage disturbance, and (ii) missing plant cover with high residue input. Otherwise, higher above- and belowground residue inputs for miscanthus than that for meadow may have contributed to a reduction in bulk density at the miscanthus plots. Absence of heavy machinery traffic, such as during tillage, herbicide and fertilizer applications, in particular, can also result in a reduction in bulk density (Jacinthe and Lal 2006).

In 2017, MWD in 0-10 cm (0-4 in) depth of the soil aggregates at the plots under miscanthus and the bare soil plots was lower than that at the meadow plots (Table 4). Among the reasons for the low MWD at the miscanthus plots may be the repeated tillage during land preparation for rhizomes planting (Guzman and Al-Kaisi 2010). In contrast, in 2018 values for MWD were generally higher and comparable among the three land uses. The general increase in MWD indicates improved soil structure under the three land uses (Hamza and Anderson 2005). Apparently, soil aggregate formation was promoted at all plots but with stronger enhancement under miscanthus as biomass and associated residue inputs were high which promotes soil life and, thus, development of soil aggregates in the absence of soil disturbance. Otherwise, the soil aggregate formation at the bare plots may have recovered from previous tillage disturbance. Thus, despite lower residue inputs compared to meadow and miscanthus, MWD also increased at the bare plots. The generally higher MWD at all plots likely contributes to an improvement in soil structure and to the resistance to soil erosion (Hamza and Anderson 2005).

Soil organic carbon and total nitrogen concentrations

The mean SOC concentrations in 0-10 and 10-20 cm (0-4 and 4-8 in) depths for 2017 and 2018 are shown in Table 5. There were no differences in SOC concentrations between meadow and miscanthus plots at the start of the experimental period. However, after the 2018 growing season SOC concentrations in 0-10 cm depth under meadow were higher compared to that for miscanthus. Also, there was a tendency that SOC concentrations increased with effluent addition, particularly, in 0-10 cm depth, but variability was also high. Guzman et al. (2017) reported that the application of effluent to miscanthus plots increased CO_2-C emissions but C input from the effluent was also retained in the soil and may have contributed to the increase in SOC concentrations observed here. The SOC is quickly lost by soil disturbance but only slowly recovers to previous levels if at all (Poeplau et al. 2011). Thus, much longer monitoring periods of decades with repeated measurements every 5 to 10 years are needed to determine the effects of land-use change from meadow to miscanthus and of effluent/fertilizer application on SOC concentrations (Johnston et al. 2017).

Table 5. Mean soil organic carbon (SOC) concentrations (% C) in 0-10 and 10-20 cm (0-4 and 4-8 in) depths for the reclaimed mine soil under meadow and miscanthus in 2017, and in 2018 separated for control and effluent addition plots (standard deviations in brackets).

Soil depth (cm/in)	Meadow		Miscanthus	
	2017	2018	2017	2018
0-10/0-4	2.2 (0.2)	2.8 (0.5) control	2.2 (0.4)	2.0 (0.4) control
		3.1 (0.4) effluent		2.3 (0.6) effluent
10-20/4-8	1.0 (0.3)	1.1 (0.3) control	1.2 (0.2)	1.3 (0.5) control
		1.4 (0.4) effluent		1.4 (0.9) effluent

The initial differences in TN concentrations in 0-10 and 10-20 cm (0-4 and 4-8 in) depths between meadow and miscanthus were small and independent of effluent additions (Table 6). Guzman et al. (2017) reported that effluent additions increased N_2O-N emissions but it was unclear whether this will result in lower TN concentrations. As year-to-year variations in TN concentrations were high, measurements in subsequent years are needed to differentiate land-use and treatment-related effects on TN concentrations similar to those for SOC concentrations (Johnston et al. 2017).

Table 6. Mean total nitrogen (TN) concentrations (% N) in 0-10 and 10-20 cm (0-4 and 4-8 in) depths for the reclaimed mine soil under meadow and miscanthus in 2017, and in 2018 separated for control and effluent addition plots (standard deviations in brackets).

Soil depth (in)	Meadow		Miscanthus	
	2017	2018	2017	2018
0-4	0.21 (0.08)	0.25 (0.04) control	0.19 (0.10)	0.15 (0.02) control
		0.27 (0.06) effluent		0.17 (0.06) effluent
4-8	0.09 (0.03)	0.09 (0.03) control	0.11 (0.08)	0.10 (0.03) control
		0.13 (0.02) effluent		0.11 (0.06) effluent

Objective 2: Evaluate the effectiveness of previous mine soil reclamation and post reclamation practices on surface and subsurface hydrology, soil hydrological properties, and soil quality.

Precipitation, air temperature patterns and soil hydrological properties

Precipitation and temperature distribution patterns for 2017 and 2018 are shown in Fig. 5 based on data from the nearest weather station at Zanesville Municipal Airport (KZZV). The temperature minima and maxima over both growing seasons from April to November were comparable to historical data. However, precipitation in the 2017 growing season was 6% higher, and that in the 2018 growing season 40% higher than the long-term average. This relatively high water input may have affected hydrological fluxes at the experimental site. Nevertheless, runoff in 2018 after major precipitation events was only increased at the bare ground plots (Table 7). Thus, precipitation distribution was also important. For example, precipitation in July 2017 (153.2 mm or 6.0 in) was much higher compared to that in July 2018 (126.2 mm or 5.0 in) while the long-term average for July is 96.3 mm (3.8 in). Average runoff at the miscanthus plots was higher and soil loss lower compared to that at the bare soil plots (Table 7). Thus, the high residue and vegetation cover at the miscanthus plots restricted infiltration during major precipitation events while it protected more strongly against surface soil loss compared to that at the bare soil plots. Hydrophobic compounds in plant leaves and roots interrupt soil water infiltration by contributing to soil water repellency (SWR; Mao et al. 2019), while plant residues on the soil surface reduce erosion-induced soil losses (Shi and Schulin 2018).

Table 7. Total precipitation and runoff water volume (cubic ft per ac), and soil loss (lb per ac) after major runoff events for bare and miscanthus land uses in 2017 and 2018 collected from runoff micro-plots using Gerlach trough.

Year	Precipitation (cubic ft per ac)	Runoff (cubic ft per ac)		Soil loss (lb per ac)	
		Bare soil	Miscanthus	Bare soil	Miscanthus
2017	64,811	8,675	16,864	9,000	640
2018	86,320	12,777	13,620	4,439	1,940

Under steady state conditions, average infiltration rates were comparable among miscanthus and bare plots but lower for miscanthus with effluent addition independent of year and assessment method (Table 8). In general, water infiltration rates were moderately rapid (0.06–0.20 cm min^{-1}; O'Neal 1952). The reason for the lower infiltration rates at miscanthus with effluent may be increased soil water repellency at the soil surface by the addition of organic compounds and biosolids present in effluent (Guzman et al. 2019; Mao et al. 2019). However, the observation of initial effects must be validated by long-term monitoring of steady-state infiltration rates.

Table 8. Average steady-state infiltration rates at the miscanthus land use without and with effluent addition, and for the bare soil in Spring 2017 and Fall 2018.

Land use	[a]Spring 2017		[b]Fall 2018	
	(cm min^{-1})	(in min^{-1})	(cm min^{-1})	(in min^{-1})
Miscanthus	0.13	0.05	0.17	0.07
Miscanthus with effluent	0.04	0.02	0.09	0.04
Bare soil	0.11	0.04	0.14	0.06

[a]Cornell Sprinkle Infiltrometer
[b]Mini Disk Infiltrometer

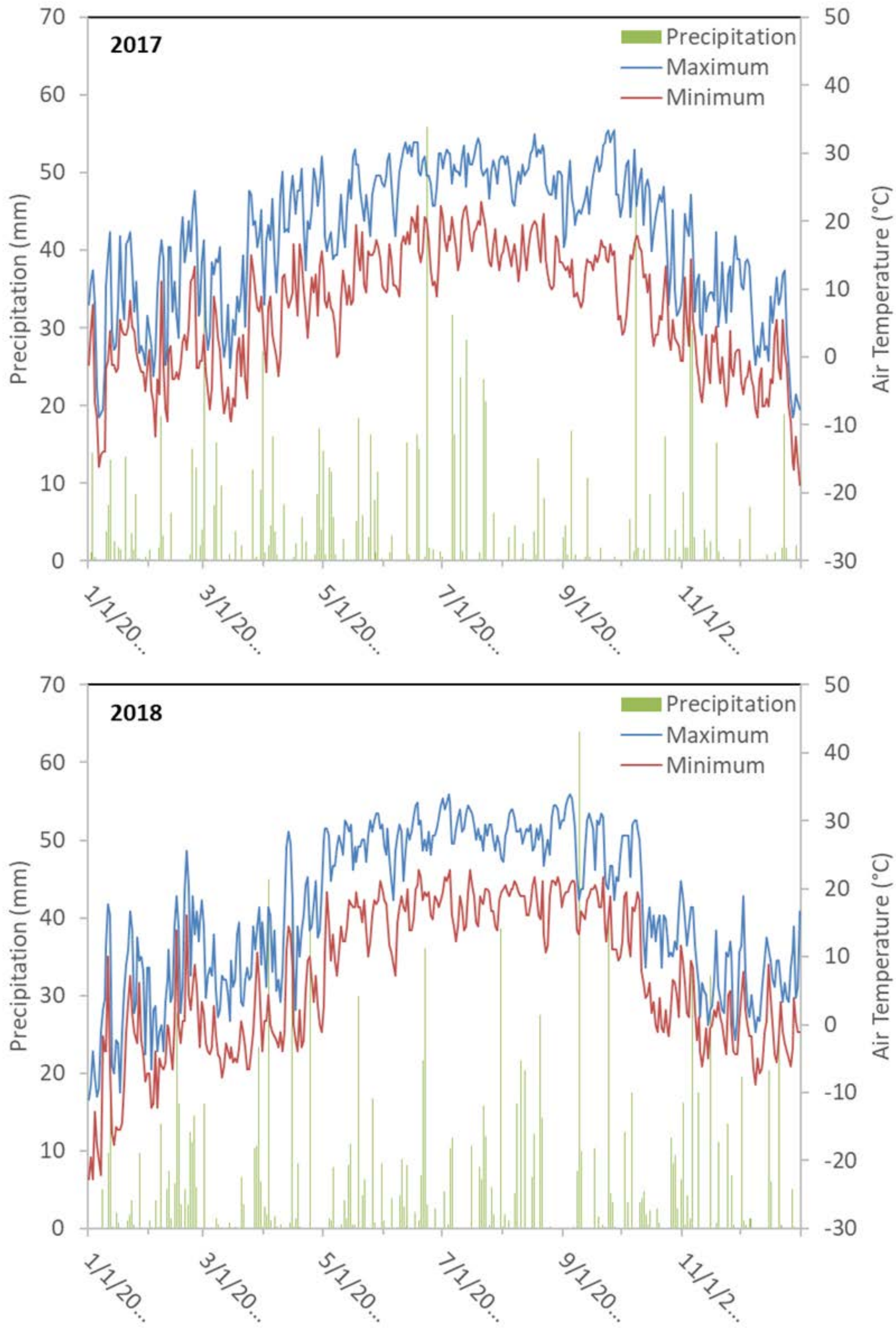

Figure 5. Monthly minimum and maximum temperatures (°C) and precipitation (10 mm = 0.39 in) in 2017 and 2018 {based on weather reports from Zanesville Municipal Airport (KZZV) weather station}

Table 9. Average soil temperatures (°F) and soil moisture contents (cubic ft per cubic ft) in 5, 15 and 25 cm (2, 6 and 10 in) depths at the bare and miscanthus plots for 2017, 2018 and the entire study period (standard deviations in brackets)

Soil depth (in)	Year	Soil temperature (°F)		Moisture content (cubic ft per cubic ft)	
		Bare	Miscanthus	Bare	Miscanthus
2	2017	56.3 (46.4)	55.0 (45.0)	0.26 (0.04)	0.31 (0.03)
	2018	57.6 (48.6)	55.4 (47.5)	0.23 (0.08)	0.27 (0.08)
	2017-2018	56.8 (47.5)	55.2 (46.2)	0.25 (0.07)	0.29 (0.04)
6	2017	56.3 (45.3)	55.0 (44.4)	0.29 (0.03)	0.30 (0.03)
	2018	57.4 (47.7)	55.6 (46.9)	0.24 (0.09)	0.29 (0.04)
	2017-2018	56.8 (46.6)	13.0 (55.4)	0.26 (0.07)	0.30 (0.04)
10	2017	55.9 (44.6)	55.2 (44.2)	0.29 (0.04)	0.28 (0.02)
	2018	57.0 (47.3)	55.4 (46.6)	0.28 (0.07)	0.27 (0.06)
	2017-2018	56.5 (45.9)	55.4 (45.3)	0.29 (0.06)	0.28 (0.05)

Soil temperature and soil moisture contents

Soil temperatures and soil moisture contents in 5, 15 and 25 cm (2, 6 and 10 in) depths were recorded every 30 minutes at the bare and miscanthus plots during the years 2017 and 2018 (Figures A1-A9; Tables A1-A4). The mean temperatures at the bare soil plots were higher at all depths compared to those at the miscanthus plots in each year, and also for the entire monitoring period (Table 9). The higher soil surface cover due to the accumulated litterfall and shading by plants provided protection from solar radiation at the miscanthus plots, and, thus, resulted in lower soil temperatures compared to that at the bare plots (Guzman et al. 2017).

The soil moisture contents differed between the bare and miscanthus plots in 5 and 15 cm depths, but were similar among land uses in 25 cm depth (Table 9). Specifically, average soil moisture contents in 5 and 15-cm depths for 2017-2018 at miscanthus plots were about 15% higher than those under bare land use. Thus, the high litter and plant soil surface cover at the miscanthus plots protected the soil against the loss of soil moisture by evaporation despite a high water uptake by development of miscanthus during the growing season (Guzman et al. 2017). However, soil moisture contents below the root zone in 25-cm depth were less affected by differences in vegetation cover.

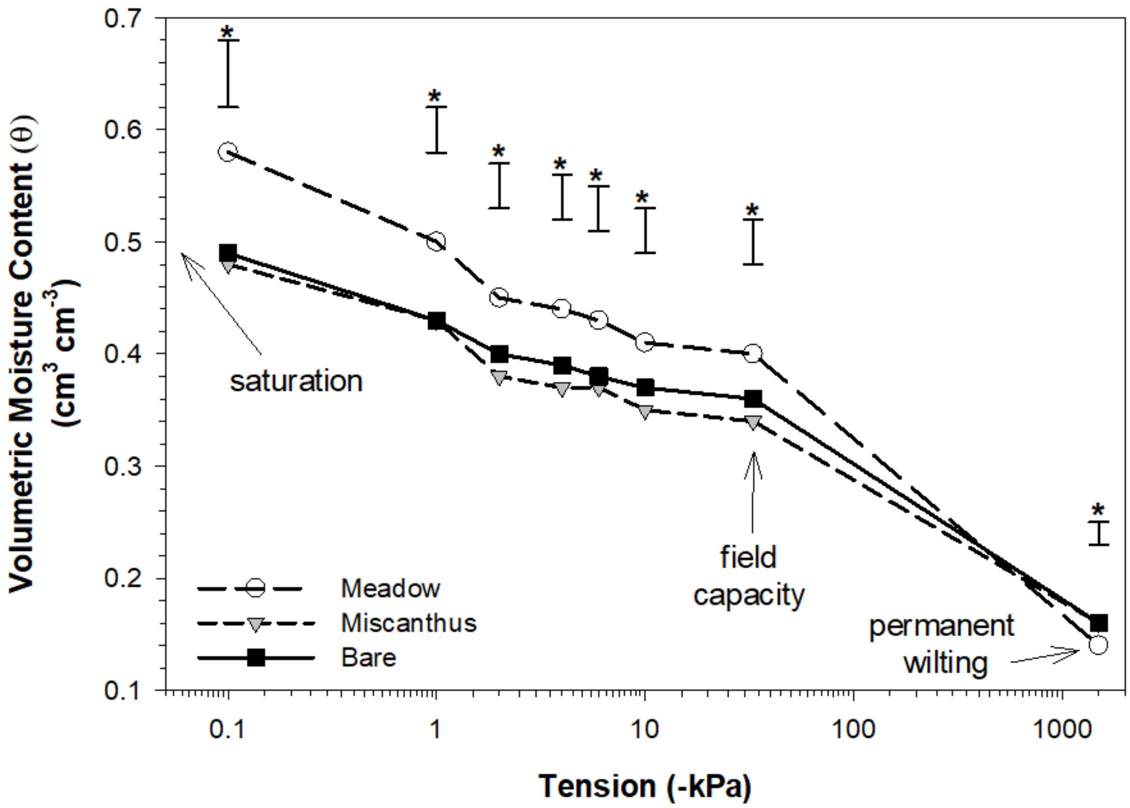

Figure 6. Soil water retention curve in reclaimed mine soil under meadow, miscanthus and bare soil for the top 10 cm (4 in) depth. Horizontal bars indicate least significant difference (LSD) values, means are significantly different at $p \leq 0.05$ within each soil depth when an asterisk is shown.

Objective 3: Establish relationship between surface and subsurface hydrological characteristics with root growth, soil properties, and SOC changes in reclaimed mine soils.

The previous study indicated that severe restriction to root penetration occurred in 35 cm soil depth at the meadow and miscanthus land-uses (Guzman et al. 2019). This trend was supported by root density measurements with the sequential biomass coring method conducted at the end of growing seasons for 0 to 100 cm depth, showing that 90 to 95% of the total root biomass occurred in the top 20 cm layer across all land-uses (data not shown; Guzman et al. 2019). However, estimating root growth and production is difficult due to multiple potential biases associated with the methods used (Milchunas 2009). Much of the literature for root production is based on sequential biomass coring, a method resulting in erroneous estimates. Multiple methods are recommended for yielding realistic estimates of root production (Addo-Danso et al. 2016). Thus, statistical analyses were not performed due to the severe limitations for root growth and insufficient root sampling design. However, favorable soil hydrological properties have generally the potential to facilitate proliferation of plant roots, and, thus, improve soil properties including increases in SOC contents (Thompson et al. 1987). The hydrologic properties at the meadow plots were better than that at bare and miscanthus plots indicated by lower bulk densities and higher contents of plant available water (Table 4; Fig. 6). Vehicular traffic and tillage disturbance at the establishment of the miscanthus and corn (now bare) plots in 2013 may have contributed to the less favorable hydrologic properties compared to that at the meadow plots which were relatively undisturbed for 30 years (Sencindiver and Ammons 2000). However, differences between plots in soil hydrological properties at deeper depths were smaller as were those for SOC concentrations. Thus, more intense exploration of the soil profile by miscanthus *vs.* those by meadow roots may potentially result in the accumulation of SOC at depth, and this should be assessed in subsequent years by also using multiple methods for estimating root production (e.g., pulse-isotope turnover and minirhizotron methods; Milchunas 2009). The deep-rooted grass miscanthus has a higher potential to improve soil profile properties than the shallow-rooted meadow plant community (Neukirchen et al. 1999). This deep-rooting is also expected to benefit soil profile hydrological properties in the long-term and enhance soil resilience (Lewandowski et al. 2003).

Objective 4: Measure and budget potential water pollutants such as leaching and surface water runoff of N and P from effluent applications.

Major surface water runoff and soil loss events were monitored in 2017 and 2018 at the bare soil and the miscanthus plots. A large temporal variability was found, i.e., total runoff was as twice as high at miscanthus plots compared to that at bare soil in 2017 while runoff volumes were similar for both land uses in 2018 (Table 7). Among the possible explanation is that not all major runoff events were monitored, i.e., those occurring at night, during weekends and holidays. Assuming that this did not play a role, the thicker surface leaf litter residue cover at the miscanthus plots may have contributed to reduced infiltration and higher surface runoff, especially in years with more intense precipitation events such as those occurring in summer 2017 (Guzman et al. 2017). However, soil loss was reduced at the miscanthus compared to that at the bare soil plots in both years as residue cover and roots in the top soil apparently protected the miscanthus plots against surface soil loss after major runoff events (Guzman et al. 2019). Nevertheless, a more complete capture of major runoff events (e.g., by using automatic sampling devices), and a longer monitoring period is needed to test the validity of these assumptions regarding the superior effects of miscanthus for reducing soil loss.

Table 10. Total loss of nitrate (lb N per ac) and orthophosphate (lb P per ac) with surface runoff water after major rainfall and runoff events in 2017 and 2018.

Year	Nitrate (lb N per ac)			Orthophosphate (lb P per ac)		
	Bare	Miscanthus (control)	Miscanthus (effluent)	Bare	Miscanthus (control)	Miscanthus (effluent)
2017	0.06	0.39	1.46	0.04	0.17	1.14
2018	0.00	0.00	0.01	0.00	0.00	0.01

The total surface losses of nitrate and orthophosphate after major precipitation and runoff events were an order of magnitude higher in 2017 compared to those in 2018 (Tables 10 and D1). Interpretation of the reasons for this large variability is challenging as differences in total runoff and soil loss between both years were much smaller. However, not all major runoff events and, thus, nitrate and orthophosphate losses may have been captured. Assuming that all major events were monitored in both years, total nitrate and orthophosphate losses were higher at the unfertilized miscanthus control plots *vs.* those at the bare soil plots. This can be explained by higher amounts of leachable N and P in surface residues at the miscanthus control plots (Guzman and Lal 2014). Even higher residual amounts of leachable N and P from previous effluent applications were present at the effluent-treated miscanthus plots, and those contributed to high nitrate and orthophosphate losses (Guzman et al. 2017). However, long-term trends should be monitored as, on one hand, increases in N and P removal with the increased miscanthus biomass harvested as bioenergy feedstock may result in lower amounts of leachable N and P. Otherwise, miscanthus is known to conserve N and P by transferring both into rhizomes at the end of the growing season (Guzman and Lal 2014). Thus, N and P demand is generally lower than that for meadow and other vegetation which may result in increasing N and P leaching from effluent-treated miscanthus plots into the environment in subsequent years and decades.

Conclusion

Growing miscanthus on reclaimed mine land in Ohio is a promising strategy to produce biomass for bioenergy as biomass yield of this perennial C4 grass was three-times higher than that of meadow. Miscanthus has also the potential to improve soil health, in particular, at deeper soil depths as root biomass was greater compared to that of meadow. Soil health properties including soil bulk density and MWD of soil aggregates in topsoil did improve with cultivating miscanthus which may enhance soil structure and resistance to soil erosion. However, no increases in SOC concentrations in the study period were observed for miscanthus. Long-term monitoring with repeated measurements every 5 to 10 years is needed to check whether the high miscanthus biomass will be associated with an increase in SOC concentration in subsequent years. Otherwise, SOC concentrations in topsoil layers tended to increase after effluent addition at the miscanthus plots. However, CO_2 and N_2O emissions from the miscanthus soil may have also increased following effluent addition as was observed in the previous study. Further, the risk of nitrate and orthophosphate losses from the effluent-treated miscanthus plots to aquatic ecosystems was also enhanced. Thus, careful monitoring and probably adjusting of effluent application rates in subsequent years is needed to reduce the risk of increased CO_2 and N_2O emissions, and N and P release into the environment, and to enhance N and P recycling between miscanthus biomass and effluent production in the anaerobic digester. While this study assessed the initial effects of miscanthus production on a reclaimed mine soil, long-term monitoring of the environmental effects is needed for a conclusive assessment.

Recommendations for the coal mining community

Miscanthus can be successfully established on reclaimed mine land that was previously under long-term meadow land use. Initially, no fertilization may be needed as miscanthus effectively conserves N and P from the previous land use in belowground rhizomes. However, whether supplemental fertilizer addition is needed in subsequent years depends on N and P removal with biomass harvest for bioenergy. Some soil health properties in topsoil also improved with time under miscanthus cultivation, and subsoil health is expected to improve in the future as this deep-rooted grass will increasingly explore the soil profile. It is also evident that soil compaction, particularly, in the subsoil should be reduced during site establishment, tillage disturbance of reclaimed mine soils should be kept to a minimum, and that reclaimed soils should never be left bare and un-vegetated to reduce leachable nutrient and soil erosion losses.

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Poster

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Appendix A. Soil physical and hydrological properties for specific sampling dates

Temporal changes in soil moisture

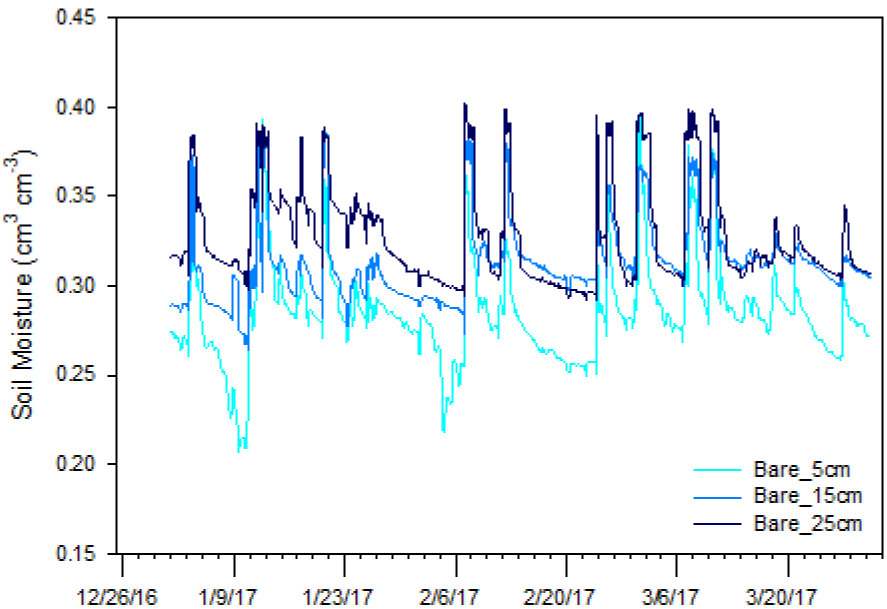

Figure A1. Temporal changes in soil moisture by soil depth in bare soil during the first quarter in 2017.

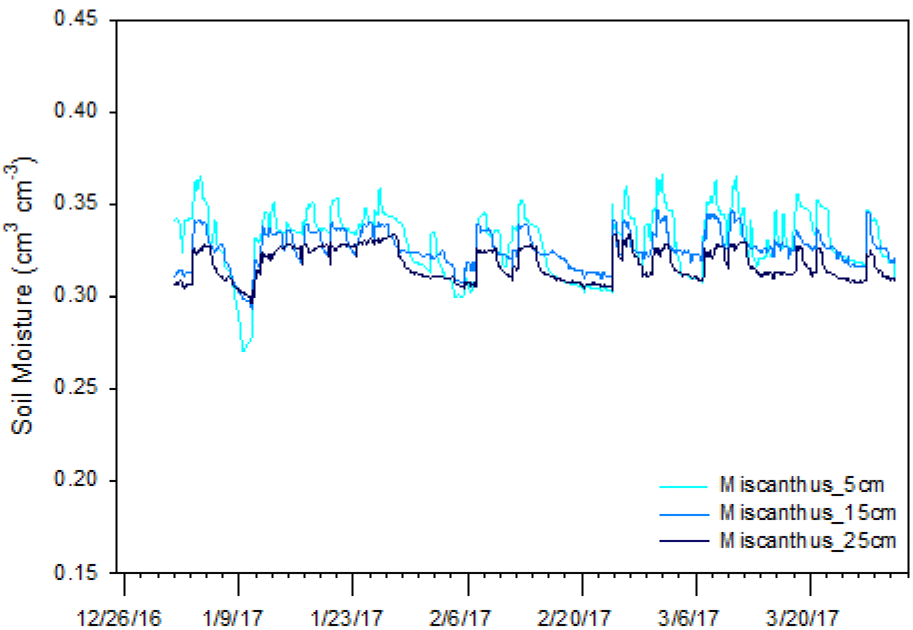

Figure A2. Temporal changes in soil moisture by soil depth under miscanthus land use during the first quarter in 2017.

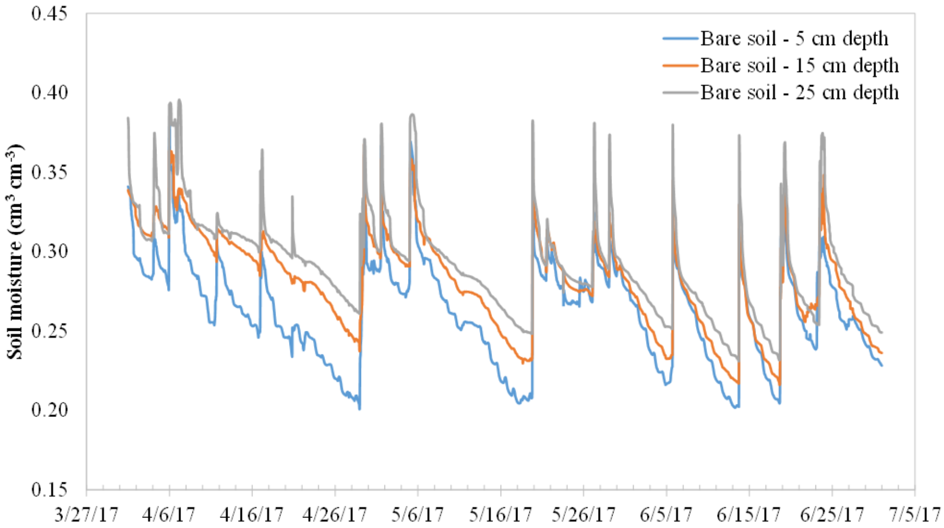

Figure A3. Temporal changes in soil moisture by soil depth in bare soil during the second quarter in 2017.

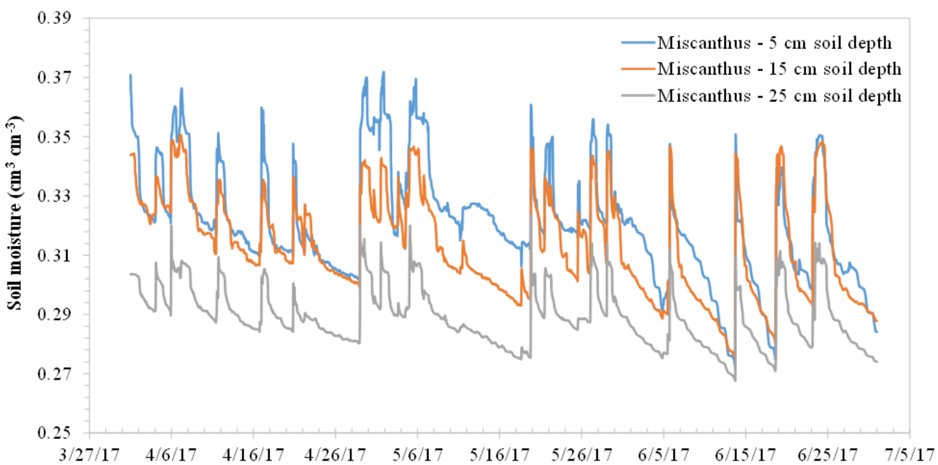

Figure A4. Temporal changes in soil moisture by soil depth under miscanthus land use during the second quarter in 2017.

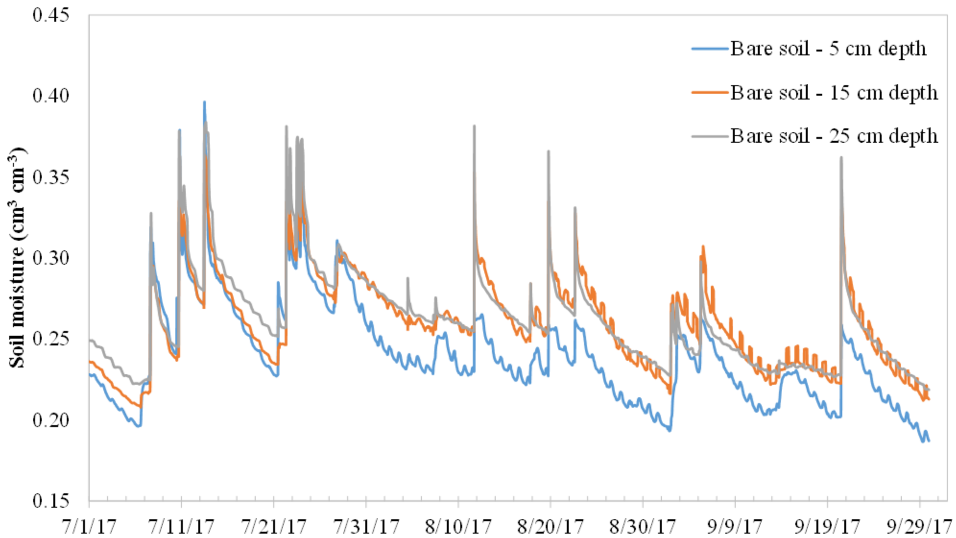

Figure A5. Temporal changes in soil moisture by soil depth in bare soil during the third quarter in 2017.

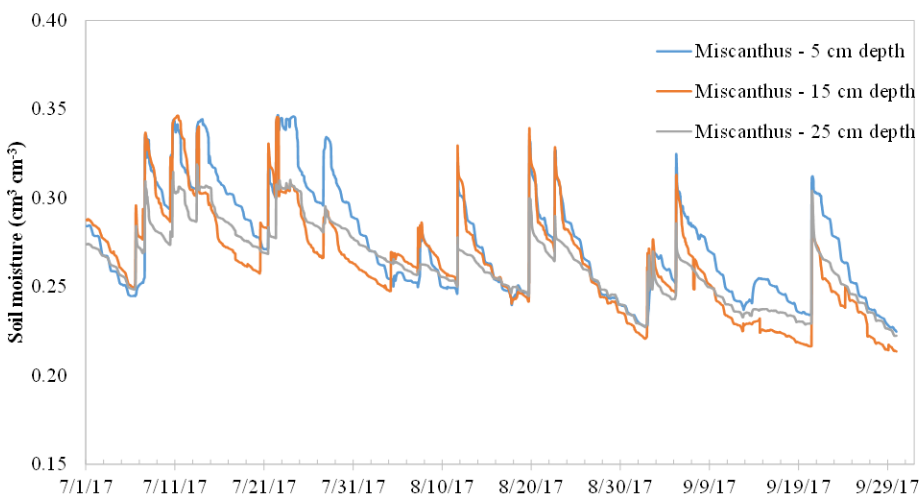

Figure A6. Temporal changes in soil moisture by soil depth under miscanthus land use during the third quarter in 2017.

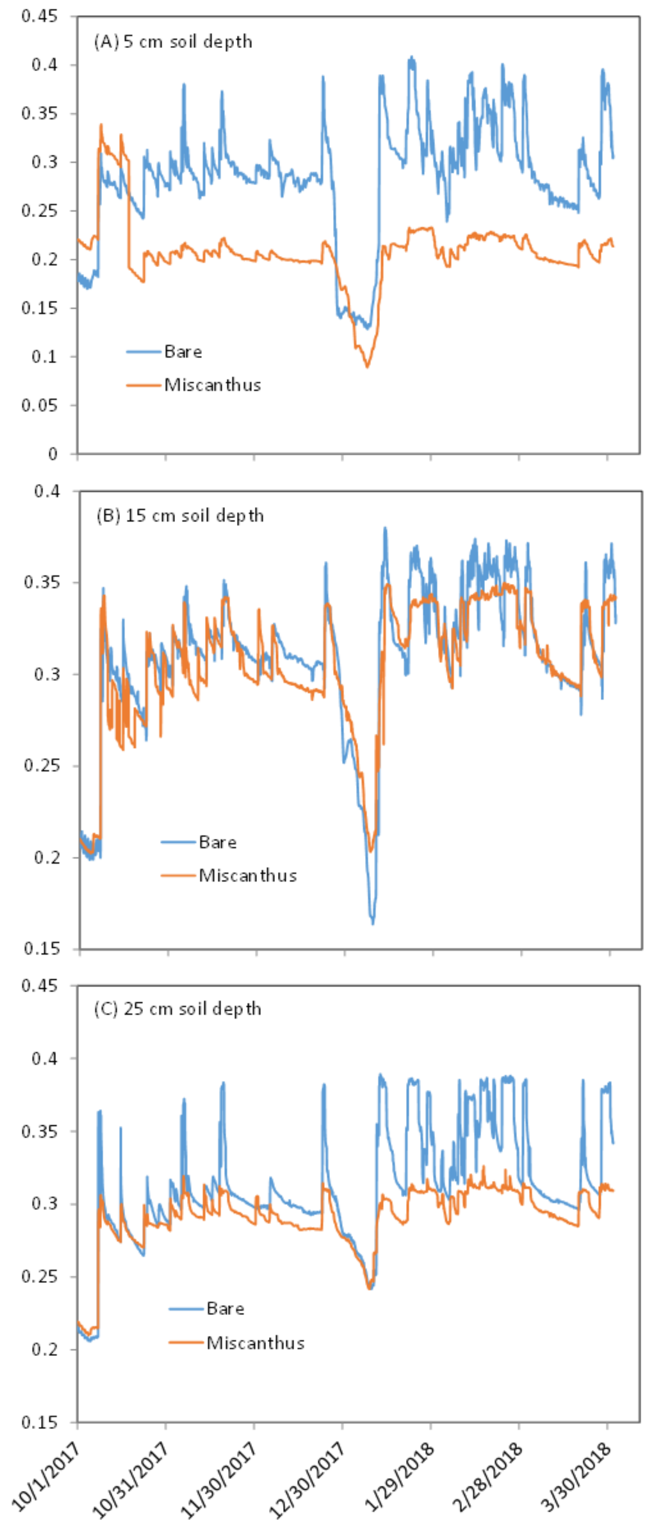

Figure A7. Temporal changes in soil moisture ($cm^3\ cm^{-3}$) at 5 cm (A), 15 cm (B) and 25 cm (C) soil depths under bare and miscanthus land uses during the fourth quarter in 2017 and the first quarter in 2018.

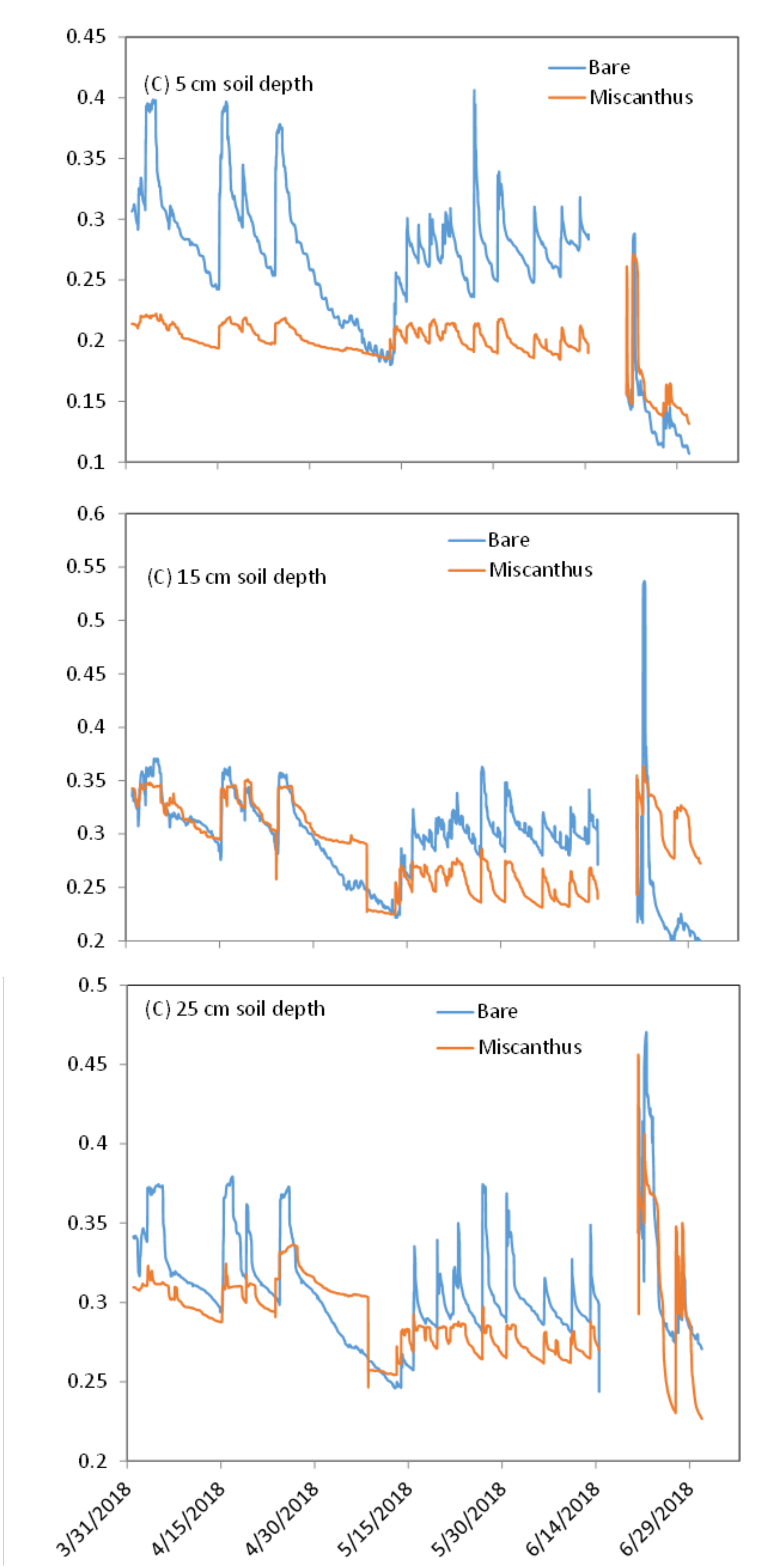

Figure A8. Temporal changes in soil moisture (cm^3 cm^{-3}) at 5 cm (A), 15 cm (B) and 25 cm (C) soil depths under bare and miscanthus land uses during the second quarter in 2018.

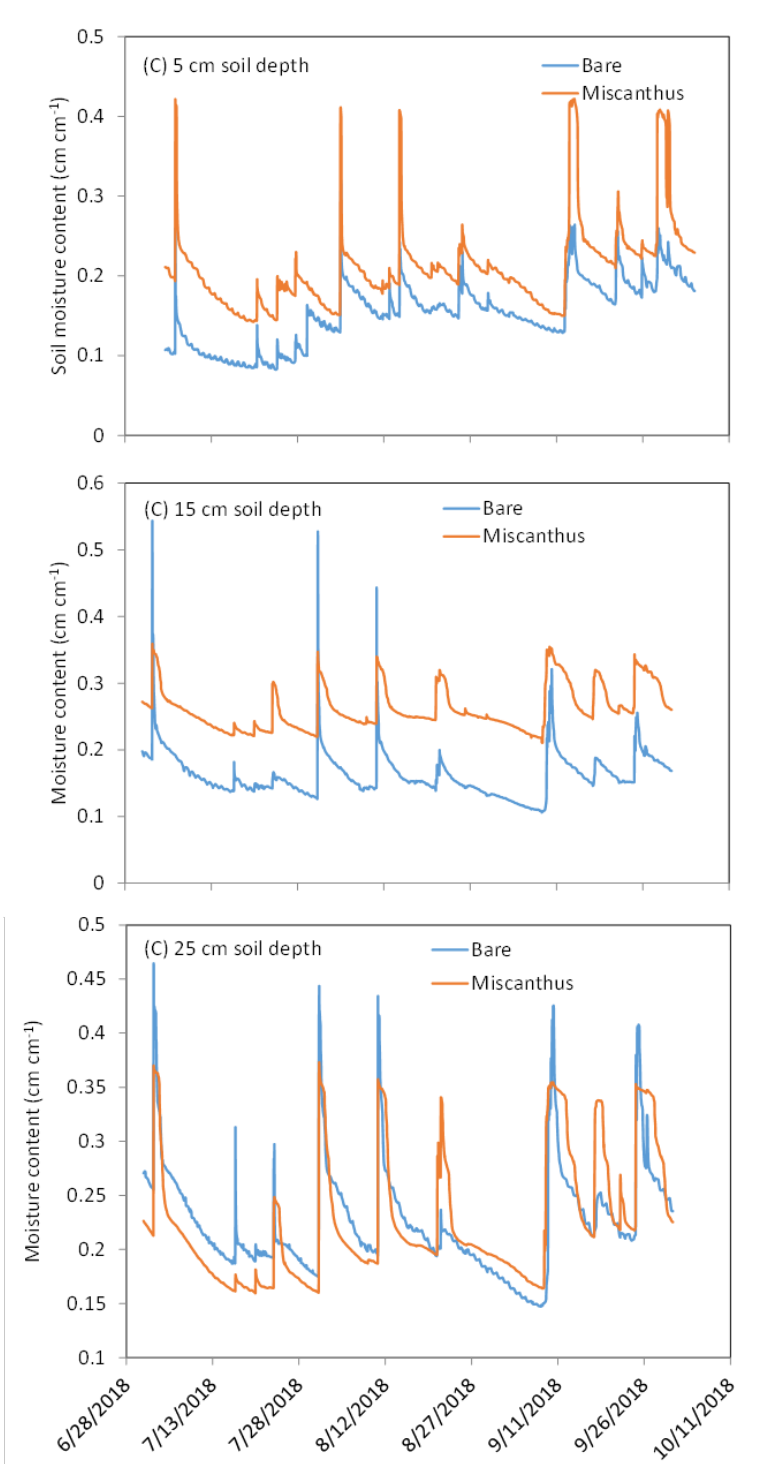

Figure A9. Temporal changes in soil moisture (cm^3 cm^{-3}) at 5 cm (A), 15 cm (B) and 25 cm (C) soil depths under bare and miscanthus land uses during the third quarter in 2018.

Monthly averages in soil moisture and temperature

Table A1. Monthly averages and ranges in soil temperature and moisture contents for the top 5 cm soil depth under bare and miscanthus land uses during the period October 2017 to March 2018.

Month		Temperature (°C)		Moisture ($cm^3\ cm^{-3}$)	
		Bare	Miscanthus	Bare	Miscanthus
October	Average	15.10	14.71	0.25	0.24
	Minimum	5.10	7.83	0.17	0.18
	Maximum	23.60	19.83	0.31	0.34
November	Average	6.95	7.40	0.29	0.21
	Minimum	2.10	3.70	0.26	0.20
	Maximum	16.90	14.23	0.38	0.22
December	Average	2.53	3.30	0.27	0.20
	Minimum	-0.70	0.97	0.14	0.16
	Maximum	8.15	7.00	0.39	0.22
January	Average	1.25	1.03	0.27	0.18
	Minimum	-1.45	-0.27	0.13	0.09
	Maximum	6.95	2.70	0.41	0.23
February	Average	4.64	3.57	0.33	0.22
	Minimum	0.65	0.97	0.24	0.19
	Maximum	15.45	8.77	0.40	0.23
March	Average	5.98	5.71	0.28	0.21
	Minimum	-1.45	-0.27	0.25	0.09
	Maximum	23.60	19.83	0.41	0.34

Table A2. Monthly averages and ranges in soil temperature and moisture contents in 5, 15 and 25 cm soil depth under bare and miscanthus land uses during the period April to June 2018.

Month		5 cm depth				15 cm depth				25 cm depth			
		Temperature (°C)		Moisture ($cm^3\ cm^{-3}$)		Temperature (°C)		Moisture ($cm^3\ cm^{-3}$)		Temperature (°C)		Moisture ($cm^3\ cm^{-3}$)	
		Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus
April	Av	9.95	8.17	0.30	0.21	9.67	8.04	0.32	0.32	9.21	8.09	0.33	0.28
	Min	2.75	4.23	0.24	0.19	4.50	4.50	0.28	0.26	5.43	5.00	0.29	0.07
	Max	19.55	12.37	0.40	0.22	15.53	11.93	0.37	0.35	13.30	11.37	0.38	0.42
May	Av	20.28	18.34	0.25	0.20	19.33	17.60	0.28	0.26	18.13	16.94	0.29	0.27
	Min	7.80	8.87	0.18	0.19	9.53	8.95	0.22	0.22	10.33	9.20	0.25	0.09
	Max	27.50	24.47	0.41	0.22	24.50	22.80	0.36	0.30	22.20	21.73	0.37	0.36
June	Av	22.09	21.26	0.22	0.18	21.74	21.06	0.27	0.27	21.22	20.66	0.31	0.28
	Min	14.53	15.40	0.11	0.13	15.73	16.40	0.19	0.23	16.37	16.93	0.24	0.07
	Max	33.27	27.77	0.32	0.27	28.80	26.20	0.54	0.36	26.60	24.40	0.47	0.46

Table A3. Monthly averages and ranges in soil temperature and moisture contents in 5, 15 and 25 cm soil depth under bare and miscanthus land uses during the period July to September 2018.

Month	Range	5 cm depth				15 cm depth				25 cm depth			
		Temperature (°C)		Moisture (cm^3 cm^{-3})		Temperature (°C)		Moisture (cm^3 cm^{-3})		Temperature (°C)		Moisture (cm^3 cm^{-3})	
		Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus
July	Av	26.23	23.15	0.11	0.18	25.64	23.03	0.16	0.25	25.18	22.58	0.22	0.20
	Min	19.17	18.50	0.08	0.14	21.53	20.13	0.13	0.22	21.83	20.50	0.17	0.16
	Max	35.60	29.07	0.32	0.42	30.57	26.60	0.54	0.36	28.37	25.10	0.46	0.37
August	Av	23.90	22.49	0.17	0.21	23.58	22.43	0.16	0.26	23.36	22.05	0.22	0.22
	Min	18.03	17.27	0.15	0.18	19.70	18.87	0.13	0.24	20.43	19.40	0.17	0.19
	Max	30.50	27.37	0.24	0.41	27.27	25.03	0.44	0.34	26.13	23.93	0.43	0.36
September	Av	21.41	20.56	0.18	0.24	21.44	20.84	0.16	0.28	21.41	20.70	0.23	0.26
	Min	14.87	14.47	0.13	0.15	16.40	15.93	0.11	0.21	17.23	16.60	0.15	0.16
	Max	27.50	25.97	0.26	0.42	25.63	24.70	0.32	0.35	24.63	23.73	0.43	0.35

Table A4. Monthly averages and ranges in soil temperature and moisture contents in 5, 15 and 25 cm soil depth under bare and miscanthus land uses during the period October to November 2018.

Month	Range	5 cm depth				15 cm depth				25 cm depth			
		Moisture (cm^3 cm^{-3})		Temperature (°C)		Moisture (cm^3 cm^{-3})		Temperature (°C)		Moisture (cm^3 cm^{-3})		Temperature (°C)	
		Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus	Bare	Miscanthus
October	Av	0.20	0.16	14.61	13.47	0.16	0.28	15.12	14.22	0.25	0.26	15.44	14.53
	Min	0.17	0.13	5.27	5.77	0.13	0.25	8.25	7.90	0.22	0.21	9.30	8.97
	Max	0.26	0.27	26.53	22.27	0.20	0.34	22.75	21.33	0.34	0.35	22.27	20.70
November	Av	0.23	0.21	6.34	6.00	0.21	0.33	7.12	6.92	0.32	0.34	7.67	7.38
	Min	0.20	0.15	1.80	1.77	0.16	0.31	3.20	3.17	0.26	0.29	4.00	3.93
	Max	0.42	0.27	15.20	13.30	0.58	0.37	13.35	12.90	0.47	0.37	13.30	12.63

Table A5. Mean bulk density per land use and depth before (Fall 2016) and two years after plot establishment (Fall 2018).

Depth			(g cm^{-3})			
(cm)	Fall 2016			Fall 2018		
	Meadow	Miscanthus	Corn	Meadow	Miscanthus	Bare
0-10	1.15	1.25	1.25	1.18	1.14	1.29
10-20	1.42	1.43	1.52	1.48	1.27	1.56
20-30	1.45	1.41	1.58	1.46	1.33	1.61
30-40	1.64	1.60	1.63	1.67	1.52	1.67

Depth			(lb ft^{-3})			
(in)	Fall 2016			Fall 2018		
	Meadow	Miscanthus	Corn	Meadow	Miscanthus	Bare
0-4	71.8	78.0	78.0	73.7	71.2	80.5
4-8	88.6	89.3	94.9	92.4	79.3	97.4
8-12	90.5	88.0	98.6	91.1	83.0	100.5
12-16	102.4	99.9	101.8	104.3	94.9	104.3

Table A6. Mean weight diameter (MWD) and mean percentages of water stable aggregation (WSA) per depth for each plot in Fall 2018.

Plot	Depth		MWD		WSA
	(cm)	(in)	(mm)	(in)	(%)
101	0-10	0-4	4.04	0.16	86
101	10-20	4-8	3.58	0.14	85
103	0-10	0-4	2.90	0.11	80
103	10-20	4-8	0.80	0.03	34
107	0-10	0-4	3.87	0.15	91
107	10-20	4-8	2.10	0.08	47
109	0-10	0-4	3.32	0.13	77
109	10-20	4-8	2.03	0.08	57
112	0-10	0-4	2.23	0.09	65
112	10-20	4-8	1.20	0.05	51
201	0-10	0-4	1.41	0.06	56
201	10-20	4-8	2.94	0.12	79
206	0-10	0-4	2.53	0.10	69
206	10-20	4-8	5.02	0.20	93
209	0-10	0-4	2.98	0.12	77
209	10-20	4-8	3.75	0.15	81
211	0-10	0-4	1.18	0.05	33
211	10-20	4-8	3.56	0.14	82
213	0-10	0-4	2.26	0.09	69
213	10-20	4-8	3.20	0.13	76
306	0-10	0-4	2.18	0.09	66
306	10-20	4-8	1.75	0.07	55
308	0-10	0-4	2.39	0.09	70
308	10-20	4-8	1.20	0.05	45
312	0-10	0-4	3.56	0.14	80
312	10-20	4-8	3.06	0.12	77

Table A7. Steady-state infiltration rates for plots under miscanthus land use without (#101, 206, 306) and with effluent addition (#103, 201, 308), and for bare soil (#112, 201, 312).

Plot	[a]Spring 2017 (cm min^{-1})	(in min^{-1})	[b]Fall 2018 (cm min^{-1})	(in min^{-1})
101	0.17	0.07	0.19	0.07
103	0.02	0.01	0.07	0.03
112	0.19	0.07	0.20	0.08
201	0.13	0.05	0.14	0.06
206	0.19	0.07	0.22	0.09
209	0.05	0.02	0.10	0.04
306	0.04	0.02	0.10	0.04
308	0.05	0.02	0.08	0.03
312	0.02	0.01	0.10	0.04

[a]Cornell Sprinkle Infiltrometer

[b]Mini Disk Infiltrometer

Appendix B. Soil chemical properties

Table B1. Mean soil organic carbon (SOC), total nitrogen (TN) and active C fraction concentrations in 0-10 and 10-20 cm (0-4 and 4-8 in) depths in fall 2018 (± standard deviation; percentage of SOC as active C in brackets)

Land use	Treatment	0-10 cm (0-4 in)		10-20 cm (4-8 in)	
		SOC	TN	SOC	TN
		----------g kg^{-1}----------			
Miscanthus	control	19.87±4.08	1.50 ± 0.18	13.31 ± 4.66	1.01 ± 0.31
	effluent	22.99±6.11	1.72 ± 0.57	13.45 ± 8.47	1.11 ± 0.62
Meadow	control	28.43 ± 5.12	2.45 ± 0.37	10.80 ± 3.13	0.94 ± 0.30
	effluent	30.49 ± 3.52	2.72 ± 0.61	14.32 ± 3.82	1.28 ± 0.19
Bare		20.91 ± 2.00	1.95 ± 0.22	15.40 ± 4.98	1.29 ± 0.31
		Active carbon			
		----------g kg^{-1}----------			
Miscanthus	control	1.14 ± 0.11 (5.7%)		0.64 ± 0.22 (4.7%)	
	effluent	1.19 ± 0.13 (5.1%)		0.71 ± 0.37 (5.2%)	
Meadow	control	1.36 ± 0.09 (4.7%)		0.66 ± 0.22 (6.1%)	
	effluent	1.42 ± 0.02 (4.6%)		0.72 ± 0.01 (5.0%)	
Bare		1.14 ± 0.17 (5.4%)		0.74 ± 0.26 (4.8%)	

Table B2. Mean total carbon (TC), TN, coal C and SOC concentrations (%) in 0-10 and 10-20 cm (0-4 and 4-8 in) depths in Fall 2018.

Plot	Soil depth (cm)	TC	Total N	Coal C	SOC
		(%)			
101	0-10	4.4	0.17	2.1	2.3
101	10-20	4.0	0.13	2.3	1.7
103	0-10	2.5	0.13	0.6	1.9
103	10-20	2.9	0.07	2.1	0.8
107	0-10	6.6	0.27	3.4	3.2
107	10-20	7.0	0.12	5.7	1.3
109	0-10	3.4	0.23	0.6	2.8
109	10-20	3.0	0.14	1.3	1.7
112	0-10	3.9	0.17	2.0	2.0
112	10-20	4.2	0.11	3.1	1.1
201	0-10	5.8	0.20	3.8	2.0
201	10-20	5.0	0.17	2.9	2.1
206	0-10	3.5	0.13	2.0	1.5
206	10-20	6.2	0.07	5.4	0.8
209	0-10	3.9	0.24	0.9	3.0
209	10-20	3.3	0.18	1.0	2.3
211	0-10	4.5	0.22	2.0	2.5
211	10-20	7.6	0.07	6.7	0.9
213	0-10	5.7	0.32	2.4	3.3
213	10-20	4.1	0.12	3.0	1.2
306	0-10	3.2	0.15	1.0	2.1
306	10-20	3.5	0.10	2.1	1.4
308	0-10	3.1	0.15	1.0	2.1
308	10-20	4.0	0.09	3.1	0.9
312	0-10	4.3	0.22	2.0	2.3
312	10-20	3.6	0.12	2.1	1.5

Table B3. Soil pH and electrical conductivity (EC; dS m^{-1}) in 0-10 and 10-20 cm (0-4 and 4-8 in) depths in Fall 2018.

Plot	Depth (cm)	pH	EC (dS m^{-1})
101	0-10	7.44	0.685
	10-20	7.68	1.074
103	0-10	7.69	1.046
	10-20	7.81	0.721
107	0-10	7.73	0.816
	10-20	7.88	0.468
109	0-10	8.12	0.980
	10-20	8.08	0.662
112	0-10	8.22	0.631
	10-20	8.14	0.616
201	0-10	7.68	1.000
	10-20	7.81	1.311
206	0-10	8.18	0.858
	10-20	8.20	0.673
209	0-10	7.92	1.725
	10-20	7.99	0.567
211	0-10	8.00	1.307
	10-20	8.06	0.652
213	0-10	7.92	1.540
	10-20	8.09	0.525
306	0-10	7.89	1.320
	10-20	8.04	0.769
308	0-10	7.90	1.405
	10-20	7.96	0.560
312	0-10	7.96	0.624
	10-20	8.02	0.778

Appendix C. Aboveground biomass

Table C1. Aboveground biomass (Mg ha^{-1}; lb ac^{-1}) in Fall 2017 and 2018.

Plot	2017		2018	
	(Mg ha^{-1})	(tn ac^{-1})	(Mg ha^{-1})	(tn ac^{-1})
101	30.7	13.7	30.0	13.4
102	33.5	14.9	29.5	13.2
103	34.5	15.4	28.7	12.8
104	26.3	11.7	27.3	12.2
105	32.8	14.6	30.8	13.8
206	29.8	13.3	6,750.3	3,010.8
207	30.4	13.5	8,666.4	3,865.5
208	31.9	14.2	7,227.6	3,223.8
209	32.7	14.6	7,260.2	3,238.3
210	33.1	14.8	8,103.6	3,614.5
306	28.0	12.5	30.4	13.6
307	28.5	12.7	30.9	13.8
308	22.7	10.1	28.5	12.7
309	27.4	12.2	31.9	14.2
310	30.6	13.7	30.0	13.4
106	8.0	3.6	7,159.5	3,193.4
107	8.8	3.9	7,001.6	3,122.9
108	8.1	3.6	7,344.0	3,275.6
109	8.9	4.0	7,511.2	3,350.2
110	8.7	3.9	5,775.2	2,575.9
211	9.0	4.0	27.2	12.1
212	7.3	3.2	29.2	13.0
213	8.7	3.9	30.9	13.8
214	7.5	3.3	26.9	12.0
215	8.0	3.6	29.6	13.2
411	7.3	3.3	6,658.0	2,969.7
412	7.3	3.3	7,931.0	3,537.5
413	8.6	3.8	7,849.2	3,501.0
414	6.8	3.0	6,772.5	3,020.7
415	7.3	3.3	6,903.6	3,079.2

Appendix D. Nitrate and orthophosphate losses with surface runoff

Table D1. Loss of nitrate (g N ha^{-1}) and orthophosphate (g P ha^{-1}) with surface runoff water for specific major rainfall and runoff events in 2017 and 2018.

Date	Nitrate			Orthophosphate		
	Bare	Miscanthus (control)	Miscanthus (effluent)	Bare	Miscanthus (control)	Miscanthus (effluent)
1/1/2017	11.08	0	0	3.25	58.32	1.57
2/8/2017	0	194.62	0	0.03	4.24	0
3/30/2017	0	186.84	21.86	0	1.45	1.13
5/3/2017	53.26	0	245.19	0.41	5.59	0
5/9/2017	0	0	0.78	0	0	7.82
5/23/2017	0	0	167.53	1.26	2.79	6.35
6/21/2017	3.60	0	0	8.02	64.44	60.50
6/27/2017	0	0	0	0	14.20	25.24
7/20/2017	0	18.72	0	22.43	26.47	81.30
8/3/2017	0	33.81	1196.87	9.65	14.90	1092.10
4/5/2018	0.00	0	0.19	0.00	0.01	0.16
4/23/2018	0.00	0.00	0.37	0.00	0.01	0.12
5/23/2018	0.00	0.00	0.18	0	0.00	0
6/7/2018	0	0	0.07	0.00	0.00	0.01