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Soil Water Infrastructure to Eliminate Off-Site Nutrient Migration and Support Farm Profitability

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Abstract

Nutrient migration from agricultural land to freshwater resources is a fundamental global concern. The Department of Agriculture at Southeast Missouri State University has installed technology to research aspects of nutrient migration and propose mitigation strategies. The installed technologies include: 1) controlled subsurface drainage and irrigation technology, 2) a denitrification bioreactor to reduce nitrate concentrations in tile-drainage effluent, 3) an off-season water storage reservoir to capture and retain nitrate-bearing tile-drain effluent which will be applied as in-season liquid fertilizer, 4) riparian buffers, and 5) cover crops. For our beef livestock operation, we are installing a constructed wetland to capture nutrient-laden runoff from manure amended pastures associated with a confined feeding facility. Modern pasture management and row-crop nitrogen research augment the environmental stewardship potential of these infrastructures, while preserving farm profitability. The goal is to demonstrate that environmental stewardship, agriculture production and farm profitability are synergistic and may be explicitly demonstrated to the agriculture community.

Keywords

Edge of Field, Nitrate, Tile Drainage, Hypoxia, Constructed Wetlands

1. Introduction—Gulf Mexico Hypoxia Zone and Nutrient Runoff

The USA drinking water maximum nitrate contamination level is 10 mg NO_3-NL^{-1}; however, smaller nitrate concentrations may strongly support the eutrophication of surface water resources [1] [2]. Nitrate sources entering surface water resources include: 1) agricultural and urban surface runoff, 2) soil erosion, 3) subsurface tile drainage, and 4) baseflow from impacted aquifers [2] [3] [4] [5]. In Iowa, Amado *et al.* [3] documented that drainage-tile flow was the primary NO_3-N transport pathway to streams. In contrast phosphorus (P) concentrations of 76 µg P L^{-1} have been proposed as the minimum P concentration supporting P-induced eutrophication [6]. Aide *et al.* [7] provided a review and data involving Edge-of-Field technology, focusing on controlled subsurface drainage and irrigation tile system with denitrification bioreactors. Specifically, the primary goals were to: a) evaluate the nitrate-N concentrations in the tile drainage effluent under a corn-soybean rotation having typical nitrogen fertilization rates based on population and yield goals, and b) estimate nitrate-N concentration reductions after passage through a denitrification bioreactor. Aide *et al.* [8] [9] provided a perspective to mitigate nitrogen and phosphorus migration from pastures receiving manure and converting nitrogen and phosphorus to organic materials utilizing constructed wetlands.

The multifold purpose of this manuscript is: 1) to demonstrate the selection and effectiveness of environmental infrastructure to limit nutrient migration, 2) to demonstrate the potential crop yield attainment of selected environmental infrastructures, 3) to reveal the systematic approach to develop a holistic prospectus that supports a unified treatment of production agriculture, farm profitability and environmental stewardship, and 4) support the coalescing of the animal science, row crop agriculture, and horticulture disciplines to this endeavor. The main thrust of this component of the manuscript is not to detail the water and soil chemistry across all years of data recovery; rather we desire to provide critical selections of data to illustrate the effectiveness of the controlled subsurface irrigation and drainage technologies, then transition to strategies for supporting technology transfer to production agriculture.

2. Existing Crop and Animal Science Infrastructure

2.1. Crop Science Infrastructure Overview

Located in Cape Girardeau County (Missouri, USA), the David M. Barton Agriculture Research Center has a 40 ha (100 acre) controlled subsurface drainage and irrigation technology. The subsurface controlled drainage system design involves parallel tiles having 10-meter spacing. Irrigation and drainage are monitored and regulated using by stop-log boxes fitted with adjustable baffles to permit irrigation/drainage water to be added/removed throughout the system by gravity flow. The submersible pump irrigation system consists of five wells, each with capacity to provide 265 $L \cdot min^{-1}$. Irrigation applications are approximately 18.7-liter ha^{-1} min^{-1} (2-gallon $acre^{-1}$ min^{-1}). The mean annual temperature is about 13˚C (56˚F), and mean annual precipitation is about 1118 mm (44 inches).

A denitrification bioreactor was constructed June 2014. Sampling ports allow water sampling from the denitrification bioreactor at the influent and effluent tile lines. The denitrification bioreactor has dimensions of 10 meters width, 20 meters length, and 0.7 meters thick. The top of the denitrification bioreactor is approximately 0.6 meters below the soil surface. Oak (Quercus) wood chips having an approximately 5 cm (2 inch) equivalent circular diameter with 1 cm thickness constitute the denitrification bioreactor bed fill. The oak chips are continuously maintained in an anaerobic redox environment and reduce nitrate-N to N_2 (dinitrogen) via denitrification.

2.2. Soil Resources

The soils of the Wilbur series (Coarse-silty, mixed, superactive, mesic Fluvaquentic Eutrudepts) are the dominant soil in the controlled-drainage study area. Nine soil excavations with soil morphology descriptions and with soil physical and chemical data was provided by the Missouri Soil Characterization Laboratory. The pedons of the Wilbur series are very deep, moderately well-drained soils that formed in silty alluvium and display Ap-Bw-Cg horizon sequences. Saturated hydraulic conductivity is moderately high or high (4.2 to 14.1 micrometers/s), whereas permeability is moderate. The potential for surface water runoff is negligible or very low. Water table depth fluctuates between 0.5 to 0.6 meters (1.5 to 2 feet) from December through April in most years. Soil pH ranges from slightly acid (pH 6.1 to 6.5) to neutral (pH 6.6 to 7.3) in the ochric epipedons to strongly acid (pH 5.1 to 5.5) and very strongly acid (pH 4.5 to 5.0) in the Bw and upper Cg horizons. The soil organic matter contents at the soil surface are less than 2 percentand decline with increasing soil depth. The cation exchange capacity is low (<12 cmol(+) kg^{-1}) to medium (12-18 cmol(+) kg^{-1}).

2.3. Water Sampling and Analysis

Water sampling of tile-drains and the denitrification bioreactor influent and effluent ports (stop-log boxes) were conducted approximately weekly during drainage intervals. Water chemistry determinations include pH, NO_3-N, NH_4-N, phosphorus, SO_4-S, calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and chloride (Cl^-). Water analysis, biomass estimation, plant tissue and soil testing protocols are discussed in Aide *et al.* [7].

2.4. Existing Animal Science Infrastructure

The David M. Barton Agriculture Research Center has 61 ha (150 acres) of pasture and hay land supplemented with contracted land for hay production to serve the animal science initiative. The animal science initiative primarily focuses on a cow-calf program and the infrastructure includes: 1) an animal science pavilion for animal care and breeding, 2) a semiconfined feed facility and 3) a confined feed facility. A grazing paddock system consists of 56 ha (140 acres) partitioned between clover (*Trifolium pratense*), tall fescue (*Schedonorus arundinaceus*) and bermudagrass (*Cynodon spp*) pastures. The pastures have underground water conduits, equipped with freeze-preventive cattle watering outlets to provide water for grazing cattle. We can effectively utilize intensive rotational grazing for the cattle with this pasture system. Cows are seasonally provided supplemental hay and grain.

Constructed wetlands that receive overland flow from animal pastures have an innate ability to convert nutrients into plant material or support denitrification [10] [11]. We are installing a constructed wetland to receive manure and nutrient enriched surface water flow from an upland winter pasture. Manure deposition from the confined feed facility will augment the nutrient flow to the constructed wetland. The winter pasture soil has a very deep, moderately well drained soil of the Winfield series having a taxonomic classification of fine-silty, mixed, superactive, mesic Oxyaquic Hapludalfs. The silt loam texture changes to a silty clay loam texture at the E-Bt boundary of an Ap-E-Bt-Btg horizon sequence. The soil within the constructed wetland is a very deep, somewhat poorly drained soil of the Wakeland soil series that formed in silty alluvium. The taxonomic classification of the Wakeland soil series is a coarse-silty, mixed, superactive, nonacid, mesic Aeric Fluvaquents) and has an Ap-Cg horizon sequence. The vegetation within the constructed wetland consists of Missouri native species associated with wetlands. The research intentions are to mitigate nutrient runoff from manure-amended pastures.

3. Controlled Subsurface Irrigation and Drainage Technology

We have installed a controlled subsurface irrigation and drainage technology and have collected 14 years of water chemistry involving: 1) a soybean (glycine max)-corn (Zea mays) rotation, 2) different nitrogen programs, 3) highly variable weather patterns, 4) and alternating episodes of drainage and irrigation. Prior to 2008 average corn yields of the study area ranged from 62,770 to 87,870 kg ha^{-1} (100 - 140 bu ac^{-1}); however, after installation of the controlled subsurface irrigation and drainage technology corn yields averaged near 125,000 kg ha^{-1} (200 bu ac^{-1}). The substantial yield increase has been estimated to be mainly attributed to subsurface drainage rather than subsurface irrigation. The controlled drainage capacity permitted timely corn planting in May, rather than late June, thus avoiding high temperatures during anthesis.

In 2019, corn and soybeans were cultured and their drainage water chemistry was documented using twelve water sampling times, involving multiple tile-drainage effluents (**Table 1**). Ammonium-N and nitrate-N were significantly more concentrated for the corn planting than the soybean planting, a feature partially attributed to nitrogen application for corn. The maximum nitrate-N concentration in the tile drainage was approximately 10 days after post-emergence nitrogen application, a feature attributed to urea conversion to ammonium with subsequent nitrification. Sulfate and pH values were not significantly different between the corn and soybean cultures. Data not presented in **Table 1** includes phosphorus, potassium, calcium, and magnesium tile drainage

Table 1. Tile drainage nutrient concentration values.

Crop	Statistic	NH_4-N ppm	NO_3-N ppm	SO_4-S ppm	pH water
Corn	Mean	2.2	10.4	13.4	6.7
	STD	6.2	9.0	10.8	0.5
Soybean	Mean	0.5	5.6	12.7	6.6
	STD	0.6	5.1	6.0	0.9

STD is sample standard deviation using Excel as STDEV, s.

concentrations. Phosphorus averaged 1 $mg \cdot L^{-1}$ for corn and 0.2 $mg \cdot L^{-1}$ for soybeans. Similarly, potassium averaged 6 $mg \cdot L^{-1}$ and 2.8 $mg \cdot L^{-1}$ for corn and soybean, respectively. Calcium and magnesium averaged 69 $mg \cdot L^{-1}$ and 8.5 $mg \cdot L^{-1}$ for corn and 92 $mg \cdot L^{-1}$ and 13 $mg \cdot L^{-1}$ for soybeans. Concentration differences involving P, K, Ca and Mg between corn and soybean cultures likely reflect fertilization and soil differences.

Soil nitrate concentrations averaged 1 to 2 mg NO_3-N kg^{-1} prior to planting and fertilization across all soil depths. Soil data post urea placement reveals that the nitrate-N concentrations are more abundant at all incremental soil depths, illustrating that leaching is permitting nitrate-N to reach the drainage tiles (**Figure 1**).

Table 2 shows ammonium-N and nitrate-N soil concentrations at two locations and at four depths and for two-time intervals. The 5th June date was 1 week after post-emergence nitrogen application (urea) and the 6 September date was just prior to corn harvest. On June 5th most of the readily available nitrogen was NO_3-N, especially for the surface soil layer. The enhanced nitrate content reflects urea's conversion to ammonium and subsequently the conversion of ammonium to nitrate (nitrification). On 6 September, the nitrogen content declined at all depths, a feature attributed to leaching to the tile drainage system and plant uptake.

4. Denitrification Bioreactor

The denitrification bioreactor is auxiliary to the controlled-subsurface irrigation and drainage technology [7]. This denitrification technology was designed and installed to utilize nitrate-N from the tile-drainage effluent as an alternate electron acceptor for anaerobic bacteria to produce inert nitrogen gas. The denitrification bioreactor consistently reduced the influent nitrate-N concentrations (**Figure 2**). In most cases the denitrification bioreactor effectively reduced nitrate-N concentrations to less than 5 mg NO_3-N L^{-1}. The range in denitrification bioreactor influent nitrate concentration values was 1.8 to 18.7 $mg \cdot kg^{-1}$ and the range of denitrification bioreactor effluent nitrate concentration values was 1.7 to 4.9 $mg \cdot kg^{-1}$. Paired t-test analysis for the influent and effluent nitrate concentrations provided significance at 0.033. The range in the denitrification bioreactor

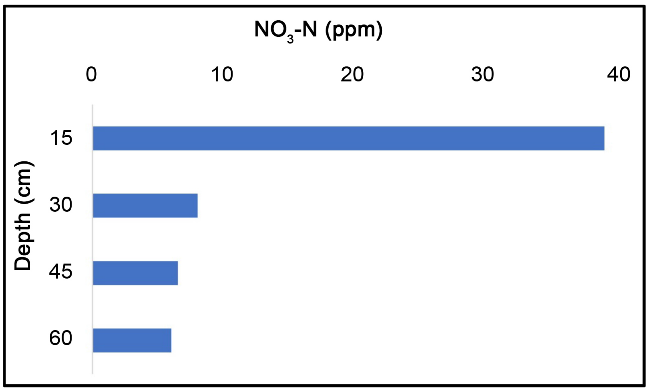

Figure 1. Soil nitrate-N concentrations in soil cultured to corn at depths of 15, 30, 45 and 60 cm several weeks post fertilizer application.

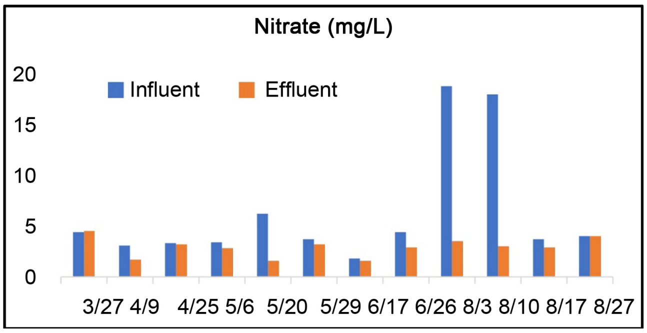

Figure 2. Nitrate-N concentrations from tile influent and effluent associated with the denitrification bioreactor (2019).

Table 2. Ammonium and nitrate soil concentrations at two locations.

Site	Depth	5 June		6 Sept	
		NH_4-N	NO_3-N	NH_4-N	NO_3-N
	cm	mg/kg	mg/kg	mg/kg	mg/kg
1	6	10.1	98.1	2.1	2.9
1	12	7.2	7.3	0.1	3.4
1	18	5.6	6.0	0.2	1.8
1	24	6.5	5.0	0.1	0.9
2	6	6.4	46.7	0.8	2.8
2	12	7.2	7.6	0.6	2.1
2	18	8.4	6.3	0.4	1.1
2	24	5.8	6.4	0.5	0.8

influent ammonium concentration values was 0.1 to 1.3 $mg\cdot kg^{-1}$ and the range of denitrification bioreactor effluent ammonium concentration values was 0.1 to 1.2 $mg\cdot kg^{-1}$. Paired t-test analysis for inlet and outlet ammonium concentrations provided insufficient significance at 0.145.

The denitrification bioreactor did not significantly alter pH, with the mean influent pH of 6.6 and the mean effluent pH of 6.3. The denitrification bioreactor did not significantly alter the ammonium (NH_4-N) concentrations (**Figure 3**). Sulfate (SO_4-S) was significantly [paired t test value of 1.6×10^{-6}] reduced from an influent mean of 13.1 $mg \cdot L^{-1}$ to 1.92 $mg \cdot L^{-1}$, suggesting the denitrification bioreactor reached a substantial anoxic intensity.

In 2016, we documented 17 observations involving paired nitrate-N tile influent and effluent concentrations showing near significant (paired t-test value of 0.056) nitrate concentration reduction.

5. Nutrient Concentration Associated with Corn and Soybean Harvest Removal and Residue Return to Soil

One attribute of nutrient management is understanding the magnitude of: 1) plant nutrient uptake, 2) nutrient partitioning among plant organs, 3) harvest removal, and 4) residue return to soil. Using plant tissue analysis (percent), dry matter partitioning, and plant population estimates, the nutrient quantitiesper land areawere estimated for various plant parts. Grain nutrient concentrations per land area (kg ha^{-1}) represent potential harvest removal, whereas the sum of the non-grain nutrient concentrations would represent potential nutrient return to the soil. **Table 3** lists the nutrient composition of grain and total plant uptake

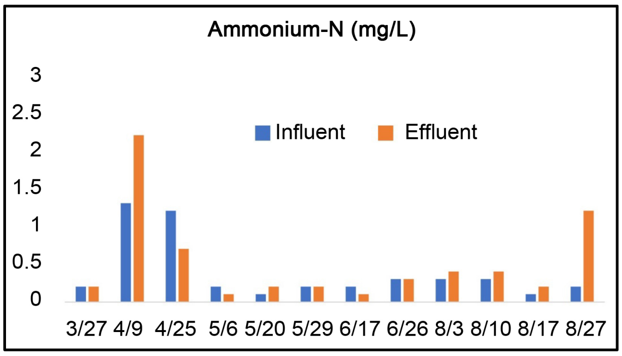

Figure 3. Ammonium-N concentrations from tile influent and effluent associated with the denitrification bioreactor (2019).

Table 3. Field nutrient uptake and potential harvest removal ($kg \cdot ha^{-1}$).

Crop/Partition	N	P	K	S
Corn				
Grain	131	37	43	11
Total	203	51	248	18
Grain/Total (%)	65	72	17	61
Soybean				
Grain	169	19	106	10
Total	265	31	161	17
Grain/Total (%)	63	61	66	59

(not including roots) in units of kg ha^{-1} for corn and soybeans, respectively. Corn nitrogen harvest removal is 65% of the total plant uptake (131 kg N ha^{-1}). Similarly, soybean nitrogen harvest removal is 63% with a total plant uptake of 265 kg N kg^{-1}. Equally important is that phosphorus and sulfur are preferentially concentrated in the grain for corn and soybeans. Potassium uptake for corn revealed that most of the potassium was associated with vegetative material, whereas for soybean a slight majority of the potassium was associated with the grain component.

6. Riparian Buffer Zones

A riparian buffer is positioned between the crop production field and Williams Creek (Figure 4). The goal of the riparian buffer is to capture runoff that is transporting nitrogen, phosphorus, and other nutrients and limiting their conveyance to freshwater resources. The riparian buffer is designed as 22.9 meters (75 ft) of trees and understory, with 7.6 meters (25 ft) of warm-season grasses.

7. Cover Crops

Cover crops are used primarily to 1) slow erosion, 2) improve soil health, 3) enhance available water capacity, 4) crowd out weeds and reduce herbicide usage, 5) reduce incidence of numerous insect and pathogen pests 6) decreased soil compaction, 7) nutrient uptake to reduce off-site nutrient migration, 8)

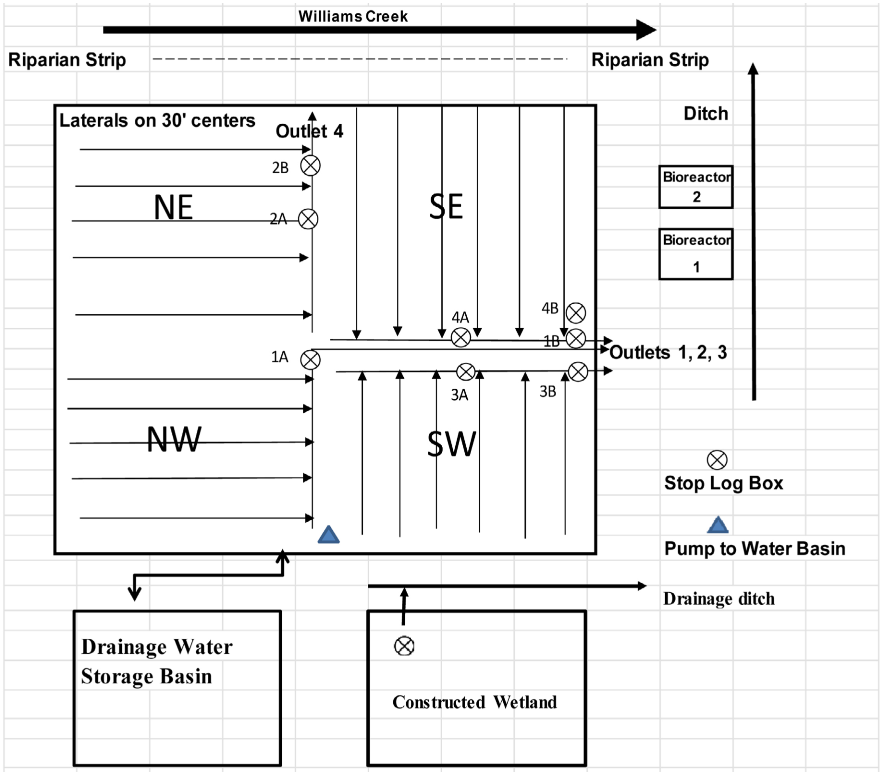

Figure 4. Infrastructure layout for the study unit. The NW, NE, SW and SE quadrants are each 10 ha.

increase soil organic matter content. The choice of cover crop to put into a system depends on many factors, including soil texture, slope, crop rotation and system, and nutrient and organic matter in the soil.

Cover crop species selected to be evaluated have included: 1) cereal rye (*Secale cereale*), 2) barley (*Hordeum vulgare*), 3) oats (*Avena sativa*), 4) wheat (*Triticum aestivum*), 5) annual ryegrass (*Lolium multiflorum*), 6) perennial ryegrass (*Lolium perenne*), 7) triticale (*Triticosecale*), 8) crimson clover (*Trifolium incarnatum*), 9) hairy vetch (*Vicia villosa*), 10) sweet clover (*Melilotus officinalis*), 11) winter pea (*Pisum sativum*), 12) oilseed radish (*Raphanus sativus*), and 13) turnip (*Brassica sp.*). Evaluations indicated that a) winter peas were not sufficiently winter hardy, b) turnips were better for animal grazing, c) oilseed radish was an excellent cover crop, d) canola was difficult to become fall established because of a narrow planting window, e) buckwheat is a summer annual that captures P and provides excellent summer weed control.

8. Cow Calf Operation Utilizing Manure Nutrient Capture Zones and a Constructed Wetland to Inhibit Nitrogen and Phosphorus Flux

Constructed treatment wetlands or "engineered wetlands" or "constructed wetlands" are designed to optimize hydrological, biological, geochemical and pedogenic processes necessary for healthy wetland ecosystems. Perceived advantages of the constructed wetland include: 1) on-site nutrient reductions [NH_4-N, organic-N, NO_3-N. total P, PO_4-P, biological oxygen demand, chemical oxygen demand], 2) odor reduction, 3) wildlife enhancements, 4) aesthetics, and 5) potential economic benefits [10] [11].

Soil quality is a relatively recent paradigm in soil science focusing on characterizing soils for their ability to support a range of attributes integral to functioning ecosystems and attempting to quantify the activity of these attributes with respect to what would be appropriate for the soil morphology [12]-[21]. Karlen *et al.* [16] defined soil quality as "the fitness of a specific soil function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". Doran and Parkin [17] defined soil quality as: "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Soil quality encompasses the following attributes or functions: 1) effectively cycling nutrients, minimizing leaching and runoff, 2) supporting t5he maintenance of water-holding capacity, 3) minimizing runoff and erosion, 4) adsorbing and filtering excess nutrients, sediments, and pollutants 5) deliveringan appropriate rooting pattern, and 6) maintenance of soil structure consistent with the soil morphology. With acceptance of these soil quality definitions, the next task implies the quantitative measurement of selective soil functions and their evaluation with respect to the soil's morphology and chemical, physical, and biological characterization. Suppose we desire to optimize a soil's water holding capacity, then it is necessary to understand that water holding capacity varies with soil texture. Thus, the maximum water holding capacity of a silt loam horizon will be starkly different than that of a loamy sand.

Soil properties may be partitioned as: 1) use-invariant soil properties which are soil properties that do not appreciably alter because of land use (texture, soil depth, clay mineralogy, cation exchange capacity, drainage class, and thermal regime), and 2) use-dependent soil properties which are soil properties that are readily influenced by land use (pH, oxidation-reduction status, electrical conductivity, nutrient status, aggregate stability, available water capacity, bulk density, infiltration, soil structure classification, the macropore-micropore distribution, enzyme activity, soil organic matter content, active carbon, soil respiration, microbial biomass, andmineralizable nitrogen) [17] [18]. These soil quality parameters (indicators) are measurable attributes (methods or protocols), which indicate the intensity of specific soil function activities [21]. As an example, the double ring infiltration method is one method for measuring infiltration, wherein two rings of different diameter are placed concentrically. The change in water level of the smaller ring is used to estimate infiltration by measurement of the water rate of fall. The purpose of the larger ring is to maintain saturated soil water conditions to prevent horizontal water movement during the time of measurement.

Developing a producer-driven soil quality monitoring program, with indicators that are either easily performed or require a low-cost laboratory analysis, is a pragmatic and effective way to engage the producer [22].

For our winter pasture which provides nutrient runoff to the constructed wetland, we have completely characterized the soil for its physical, chemical, and biological properties. Thus, we have identified the soil's use-invariant properties required to provide a perspective for assessing the quality of the use-dependent properties. We have selected the following indicators to monitor the pasture for changes in soil health: 1) rooting depth, 2) bulk density, 3) soil structure stability, 4) infiltration rate, 5) total organic carbon and nitrogen, 6) labile (active) carbon, 7) microbial carbon and nitrogen biomass, and 8) phospholipid fatty acids. Land management will support sustainable grazing to provide sufficient top growth, deep and extensive root systems, limiting soil organic matter loss, preserving soil aggregate development [23] [24] [25]. Pasture attributes that will be measured include: a) spatial distribution of plant composition b) plant mortality and residue accumulation, c) annual plant biomass accumulation, d) plant vigor by monitoring growth stage development over time, and e) plant and soil tissue sampling to assess soil fertility.

9. Connectivity of Environmental Stewardship and Farm Profitability to Support Producer Acceptance

In an era of economic restrictions, low commodity prices and increasing production costs, agricultural producers will more readily accept and install environmental technology when increased farm profitability is probable. Thus, our outreach to the agricultural community is predicated on proposing and showcasing technology that: 1) is readily incorporated into the farm operation, 2) is affordable, 3) provides appropriate information for improving land management, 4) affords environmental stewardship, and 5) supports farm profitability or engages government support programs.

Profitability for the controlled subsurface irrigation and drainage technology may be easily obtained using pre- and post-technology installation crop yields and market prices. We estimate that the controlled subsurface irrigation and drainage technology has an eight-to-nine-year payback. The denitrification bioreactor is difficult to assess, given the environmental benefits are water quality improvements downstream. When additional denitrification bioreactor installations are achieved, then a regional improvement in water quality may be provided. A similar situation occurs when considering riparian buffers; however, farm support programs are available in selected regions. Cover crops are gaining substantial acreage coverage and increasing interest across the farm belt. The improvement in soil organic matter, root penetration, reduced bulk density, and other soil features are outcomes desired by producers.

To expand our outreach to the agricultural community, we have developed robust linkages with Federal and State Agencies, other institutions of higher education, agriculture and conservation organizations, and the private sector. Currently, we are developing a social media presence.

10. Conclusion

We have identified that the following technologies are regionally suited for conserving soil and water resources: 1) controlled subsurface drainage and irrigation, 2) denitrification bioreactor, 3) riparian buffers, 4) cover crops, and 5) the constructed wetland. Each of these technologies adds to the management inventory available to promote farm profitability and environmental stewardship. We have placed these technologies in one location; such that, these technologies may support faculty research and cross-discipline endeavors. We firmly believe that plant and animal science researchers will be cooperatively involved in environmental stewardship research, given that these disciplines frequently have different research interests and goals, thus a whole farm approach may be absent without interdisciplinary collaboration. The outreach component utilizes the research infrastructure to commercialize the farmer-adaptation to support both farm profitability and environmental stewardship.

Authors' Contribution

All the authors have contributed equally to this work and share the first authorship.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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