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WATER QUALITY AND PRODUCTION POTENTIAL EFFECTS OF CELLULOSIC BIOFUEL CROPS GROWN ON MARGINAL LAND

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WATER QUALITY AND PRODUCTION POTENTIAL EFFECTS OF CELLULOSIC BIOFUEL CROPS GROWN ON MARGINAL LAND

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In loving memory of all my grandparents Don, Rosena, Frederick & Mary, Aunt DeDe and Aunt Liz. I wish you all could have been here to share in this with me. I love you now and always.

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ABSTRACT

Montgomery, Amanda Katherine. M.S., Purdue University, December 2015. Water Quality and Production Potential Effects of Cellulosic Biofuel Crops Grown on Marginal Land. Major Professors: Indrajeet Chaubey and Sylvie Brouder.

With an increasing global demand for fossil fuels, there is a growing amount of concern about greenhouse gas releases. Concurrently, interest in alternative sources of energy, including bioenergy has expanded considerably in the recent years. The Energy Independence and Security Act of 2007 mandates that 136.3 billion liters of biofuels must be produced, with 60.5 billion liters coming from cellulosic biofuel crops by 2022. Potential sources of cellulosic biomass are: maize residue, sorghum, switchgrass, *Miscanthus*, and woody crops. The increase in biofuel crop production required to meet the mandate raises questions regarding the additional amount of agricultural land area needed, as well as the potential competition for land with food and feed production. The utilization of marginal lands, lands not suitable for crop growth due to infertility, slope, soil degradation or poor yields of common annual crops such as corn, is an alternative, but could come at a higher environmental cost. There has been little field research investigating the environmental consequences of using marginal land for biofuel crop production. The objectives of this research were to quantify surface and subsurface nutrient losses and determine production potential of six crops (*Miscanthus*, switchgrass, maize, sorghum, poplar, and native prairie) when grown on marginal lands with varying rates of nitrogen (N), and varying phosphorus (P), and potassium (K) fertilizer rates or residual soil P and K levels. This study used previously-established research plots at the Throckmorton Purdue Agricultural Center (TPAC), in West Lafayette, IN. Switchgrass plots were established in 2007, *Miscanthus* in 2010, and maize and sorghum plots were established in 2011 at one site. Other plots were established in 2011. Yields were assessed in 2013 and 2014. Suction cup lysimeters permitted soil profile leachate to be sampled at a depth of approximately 30.5 cm. in a small subset of plots, and nutrient loading in surface water runoff was sampled during 2014. Surface samples were collected in tanks at the bottom of the plots. Subsurface water samples were analyzed for nitrate-N (NO_3-N) concentration and soluble reactive phosphorus (SRP) concentration, while surface runoff water samples were analyzed for NO_3-N, SRP, total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS). Subsurface leachate concentrations of NO_3-N from the perennial grass plots were significantly lower when compared to those extracted from the annual row crops. *Miscanthus* showed some leaching of phosphorus when fertilized with P fertilizer. One year of surface monitoring data indicated that surface nutrient loads were not significantly affected by crop. However, switchgrass had significantly lower nitrate loads than sorghum and *Miscanthus*. Many of the nutrient and TSS loads were higher at the start of the growing season (May) when planting and fertilization occurred as compared to later in the season after full plant growth. *Miscanthus* yield was significantly higher than all other crops in this study, averaging 22.6 t ha^{-1} on the dry weight basis. Fertilizer

rate did not make a significant difference in biomass production within a crop treatment on the plots with fertilizer trials. This study indicates perennial grasses may have markedly lower nutrient losses and can help reduce soil erosion, while also producing a significant biomass yield when grown on land considered marginal because of lower fertility and high erosivity.

CHAPTER 1. INTRODUCTION

1.1 Background

1.1.1 Global climate change

The United States (U.S.) economy was dependent on gasoline and subject to price panic from disruption in supplies, as evidenced by shortages in the 1970s and after Hurricane Katrina (Energy, 2011; Ragauskas et al., 2006). A U.S. fuel mandate in 2007 fed by an oil crisis inspired a greater focus on evaluating biofuel crop potential as an alternative fuel source. Since that time, the U.S. has increased its oil production due to the increasing practice of fracking. Currently it is predicted that there are natural gas reserves of approximately 716 trillion m^3 and domestic oil production in the U.S. is expected to increase by 15% over the next several decades (Vengosh et al., 2014). However, this increase in shale gas production has led to concern about the possible associated environmental consequences, including air pollution, greenhouse gas emissions, radiation and water contamination (Ragauskas et al., 2006; Vengosh et al., 2014). The review by Vengosh et al. (2014) notes that with the increased use of hydraulic fracturing for shale oil production, there are concerns about subsurface and surface water quality as well as concerns about water quantity. Ragauskas et al. (2006) assert that bio-based resources must replace petroleum as a part of the management of GHG emissions. One possible alternative is liquid fuels derived from plant biomass. Though research on lignocellulosic biofuels has existed since the 1970's (Ragauskas et al., 2006), just prior to the 2007 mandate, Ragauskas et al. (2006) set forth a plan for advancing biofuels in the review paper "The Path Forward for Biofuels and Biomaterials." This article reiterates why dependence on fossil fuels is unsustainable and why a push towards developing renewable fuel sources is necessary. They specify that research should be completed to improve yields and help agricultural producers to integrate biofuels into their current production system. This research, while not specifically manipulating plant genetics, tests the production potential of different biofuel crops and their performance under different fertilizer rates to help identify the crops with the greatest production potential.

1.1.2 Biofuels

Many countries, including China, France, India, Japan, the United Kingdom, and the U.S., have set mandatory or voluntary bioenergy targets for their fuel sectors (Fargione et al., 2010). Stimulating the U.S.' push toward renewable fuel sources (RFS) was the passing of the Energy Independence and Security Act (EISA) of 2007 (Congress). The EISA of 2007 enacted by the U.S. Congress set a goal of 136.3 billion liters of RFS produced by 2022; of that amount, 60.5 billion liters are required to come from cellulosic bioenergy crops (Congress, 2007). In an ISI Web of Knowledge search completed April 2015 using search terms "biofuel conversion," "biofuel environment," and "biofuel water quality," the number of research publications on biofuel conversion technologies is twice the number of research publications on the environmental effects of biofuel production and more than seven times the number of research publications on water quality and biofuel production. Research on water quality effects of biofuel crop production remains insufficient to support full-scale economic biofuel production.

The EISA encourages both empirical research and the use of analytical tools to assess environmental and economic impacts from the biofuel crop production increase (Sec. 232). Current biofuel production must be increased to meet the set standards, and therefore furthers the need to evaluate the environmental impacts that the increased biofuel production may have. Some of that increased production has been targeted to occur with dedicated, cellulosic crops grown on lands considered marginal for annual row crops (Sec. 202). While the mandate requires the production of biofuels, it also encourages determination of current and future environmental consequences and impacts (Sec. 204). The Department of Energy (DOE) is charged with setting goals for development of biofuel crops that are less resource and land intensive (Sec. 232). Research on biofuels has therefore begun to focus on the environmental impact of meeting the RFS, in addition to fuel conversion technologies.

Depending on structural constituents, biomass can be converted through different processes into many different types of fuel. Some of these final products include: biohydrogen, bioethanol, biodiesel, biomethanol, and bio-oil (Demirbas, 2007b). Ethanol and biodiesel can be derived from both grain and residue of the high-value, annual row crops traditionally grown as food or feed, and whose production requires high-quality agricultural land with lower slopes and good soil quality. However, bioethanol can be produced from an alternative cellulosic biomass such as herbaceous and woody crops, which many experts forecast may be highly productive on more marginal lands (Demirbas, 2007b). As a ratio of output to input, conversion of grass biomass can result in a 50-100% greater energy return than conventional maize biomass production (McLaughlin and Walsh, 1998). Based on a life-cycle assessment, cellulosic ethanol from switchgrass has been shown to produce 94% less GHG emissions than gasoline (Schmer et al., 2008). This versatility of processing practices and resulting products, as well as the implied environmental benefits, are the main reasons bioenergy crops have potential moving forward.

According to the EPA federal register of 2012, soybeans are currently the most used feedstock for biodiesel production and corn oil is the second most common source. These crops are logical choices for bioenergy production because of their present dominance in U.S. agriculture. In 2014, there were 36.6 million hectares of maize and 33.8 million hectares of soybeans planted in the U.S. (USDA NASS, 2015). The biodiesel conversion process from bio-oil is much more established than the ethanol conversion from cellulose. Biodiesel conversion dates back as far as the 1850s (Demirbas, 2007a).

While maize grain and stover as a biomass source are readily available due to their historic presence in U.S. agriculture, this resource alone is not sufficient to reach the

EISA goal (Energy, 2011). Second generation bioenergy crops targeted for cellulosic ethanol, such as perennial grasses, like switchgrass and *Miscanthus*, and woody plants, like *Populus* L. (poplar) and *Salix* L. (willow) trees, can provide an alternative to the traditional bioenergy crops of maize and soybean. There are a few reasons these crops are an attractive feedstock moving forward: they are a renewable resource, the crop source is readily available, they can have positive environmental benefits, and they will minimize competition with food sources (Demirbas, 2007b). While biofuel sources can be more globally spread, the benefit of ease of access may also be a downfall, as some believe they will suffer from a lack of energy density, making them less economically viable, as they will need to be collected and aggregated to produce any significant amount of bioenergy (Hoekman, 2009). The potential for low energy density, makes it a challenge to efficiently and cost effectively produce biofuels on a large scale. Currently, transportation costs are a major barrier to efficient production (Hoekman, 2009).

Many studies have evaluated the GHG emissions of biomass production (e.g., Adler et al., 2007; Bailis et al., 2005; Schlamadinger et al., 1997; Schneider and McCarl, 2003; Searchinger et al., 2008), research on its impacts on water use and water quality is limited (Wu et al., 2014). If biofuel crops are poorly managed or unsuitable for a given area, there are potential pollution challenges such as fertilizer, pesticide, or sediment losses to surface and subsurface water For example, sediment in runoff is inversely affected by soil cover and directly affected by soil disturbance, such as tilling and planting annual crops (Turner and Rabalais, 2003). Thus, maize and soybeans may result in greater sediment losses if planted in high erosion risk areas.

The primary water quality concerns associated with current agricultural systems in the Midwestern US are nitrogen (N) and phosphorus (P) from crop fertilizers, as well as soil erosion and increased runoff (Buck et al., 2004; Tong and Chen, 2002; Turner and Rabalais, 1991, 2003). The consequences of too much agricultural fertilizer run off can be readily observed in the Gulf of Mexico where a growing hypoxic zone developed in part as a result of fertilizer application to annual grain crops in the Midwest (Dominguez-Faus et al., 2009; Sahu and Gu, 2009; Wu and Liu, 2012). The quantity of water and nutrients used for biomass production, however, can vary greatly, based on feedstock, production technology, regional climate and environmental conditions, as reviewed by Wu et al. (2014). For example, Cadoux et al. (2012) indicated optimal N fertilizer rates for *Miscanthus* are 49-98 kg N ha^{-1} for a yield of 10-20 t ha^{-1}, while Vogel et al. (2002) indicated optimal N fertilizer rates for switchgrass are 50-120 kg N ha^{-1} for yields of 10-12 t ha^{-1}. These are considerably lower N fertilizer rates when compared with those commonly applied to maize, which typically requires from 110-220 kg N ha^{-1} for optimal grain yields (Vogel et al., 2002). While there have been some comparison studies of these crops, they have often been done on what is considered prime agricultural land (e.g. McIsaac et al., 2010; Trybula, 2012). There is a knowledge gap in the published research for field-scale, side-by-side comparisons of predominant biofeedstock crops (annual row crops such as soybean and maize) and second generation bioenergy crops (perennial grasses and woody crops) on marginal land, lands not suitable for intensive crop production (Thomas et al., 2014; Varvel et al., 2008). If marginal lands are to be utilized for production of cellulosic bioenergy crops, associated environmental impacts must be quantified. The potential for biomass production from second generation bioenergy crops to be less nutrient input intensive could begin to address water quality concerns in the U.S. At present, there are no other known studies examining water quality implications of maize, switchgrass, and *Miscanthus* production on marginal lands in the Midwest (Thomas et al., 2014).

1.1.3 Marginal Lands

The increase in bioenergy crop production required to meet the EISA mandate has led to concern about the amount of land needed (Escobar et al., 2009). If bioenergy crops are grown on existing food/feed crop lands, there is a potential for competition between food production and the ability to grow enough crops for bioenergy. When attempting to avoid this competition, if pastureland or retired crop land [Conservation Reserve Program (CRP) land] is dedicated to bioenergy production, the increase in agricultural land could have environmental consequences. In order to increase bioenergy production while minimizing environmental impacts, alternative land resources must be evaluated.

The amount of marginal lands feasibly available for biofuel production in the United States and the implications of using these lands for bioenergy is still uncertain (Gelfand et al., 2013). In a review by Milbrant et al. (2014), approximately 865,000 km^2 or 11% of land area in the 48 contiguous states were characterized as marginal land suitable for biomass production. These authors included abandoned crop land, abandoned mine lands, EPA sites (including Brownfield, Superfund sites, and Resource Conservation & Recovery Act sites), landfills, right-of-ways, and barren lands in their marginal land classification. Although these lands are potential candidates for biofuel production, they are often less fertile, higher sloping with greater erosion potential, and could require more nutrient inputs to produce desired yields leading to potentially higher edge-of-field nutrient losses (Thomas et al., 2014). Research by Mbonimpa et al. (2014) examined the environmental challenges that can arise from the potential loss of CRP land to continuous maize as an effort to meet the RFS. Using statistical models, the authors determined that while precipitation is a major influence on total suspended solids (TSS) and total phosphorus (TP) in streams, other factors such as land cover, soils, slope, and management practices can also play a role in environmental impact. In-field research is required to better quantify environmental risks of devoting marginal lands to bioenergy feedstock production (Thomas et al., 2014).

It is important to note that, while perennial grasses as bioenergy crops are generally anticipated to require less fertilizer and be higher producing on marginal land, this has not been conclusively demonstrated through field experimentation. Most of the existing research in this area involves environmental simulation models, with little field monitoring data available to validate them. Some of the processes associated with perennial grasses, such as greater extraction of soil water due to longer growing season, are less accurately predicted than for annual crops (Thomas et al., 2014). Cibin et al. (2015) noted the Soil Water Assessment Tool (SWAT) model does not yet accurately predict environmental water quality effects of many bioenergy crops, such as *Miscanthus* and switchgrass, and there is limited information on crop growth validation for bioenergy crops. Without this information, other poorly represented processes could include nutrient translocation within the plant, belowground nutrient storage, and extended evapotranspiration periods (Cibin et al., 2015). There are few existing studies that determine nutrient load to surface and subsurface water systems as a result of second generation biofuel crop systems (Lesur et al., 2014; Mbonimpa et al., 2014).

1.2 Overall goal

The main goal of this research was to determine the water quality impacts of growing different bioenergy crops on marginal lands and to comparatively analyze how effectively these crops produce biomass on marginal land. This research focused on six bioenergy crops: *Miscanthus*, switchgrass, poplar, a native prairie grass mix, and sorghum, using hybrid maize as a control.

1.3 Objectives

The specific objectives of this study were to:

1. Characterize subsurface nutrient losses as a result of annual and perennial bioenergy crop production.

2. Quantify sediment and nutrients in surface runoff as a result of annual and perennial bioenergy crop production.
3. Quantify the relative production potential of five cropping systems when grown on land considered marginal for maize-based annual row crop systems.

1.4 Significance of work

The data collected from this research can be used to better inform and calibrate environmental models for representing the dynamics of non-traditional biofuel crops when grown on farmland considered marginal for intensive, row crop production. These models, once adequately parameterized, can then be used to help predict the watershed scale effects of meeting the cellulosic fuel demand outlined in the EISA. Through this subsequent modeling work, results can inform decisions about where within an agricultural landscape cellulosic biofuel crops can be effectively grown with minimal water quality impact and the maximum net energy value.

CHAPTER 2. LITERATURE REVIEW

2.1 Annual row crops

At the time the EISA was promulgated, the one staple crop of the Midwest that was readily available to be converted to ethanol was maize. However, converting land from CRP land or maize-soy rotations to continuous single crop (maize or sorghum) to increase ethanol production may not be an ideal long-term solution, primarily due to environmental consequences and interference with food and feed production. Even when grown on prime agricultural lands, maize has one of the greatest fertilizer and pesticide input rates of the potential ethanol crops (Committee on Water Implications of Biofuels Production in the United States, 2008). Increasing row crop production to meet the EISA 2007 standard could result in negative environmental consequences as a result of more land being tilled and fertilized (Dominguez-Faus et al., 2009). Many environmental experts have expressed concern that extending production of annual row crops, particularly maize, will worsen the well-known nutrient pollution problems long associated with maize's predominance in the Midwest U.S (Barbieri et al., 2008; Dominguez-Faus et al., 2009; U.S. Environmental Protection Agency, 2011).

2.1.1 Maize

Maize is currently the most widely used crop for ethanol production, in part due to its prevalence (Sindelar et al., 2013). Using strictly maize production to meet the renewable fuel sources mandate will make it difficult to simultaneously meet the total maximum daily load (TMDL) limits for nutrients and soil set by the EPA in the Clean Water Act (2012) (Khanal et al., 2014). High fertilizer application, particularly in the Midwest, reduces N and P uptake efficiency (Barbieri et al., 2008). Harvesting maize stover could also have adverse effects on soil health and quality, including potential decreases in soil organic carbon and soil microbial activity, and increases in compaction, runoff and erosion (Moebius-Clune et al., 2008; Khanal et al., 2014; Sindelar et al., 2013; Thomas et al., 2014). In a study by Sindelar et al. (2013), it was shown that moderate stover removal, particularly in areas with cool early-season temperatures, can improve corn production in continuous corn systems. However, the authors caution that plans for stover removal over long time periods must consider those potential negative effects. In a recent modeling study, sediment yield to surface water increased 29% when 70% of stover was removed for use as a biofeedstock (Cibin et al., 2012). These simulated increases in sediment erosion occurred from December until plant maturity in August (Cibin et al., 2012). Nitrogen and P are the main causes of nutrient pollution problems in waterways and it is estimated that organic N and organic P loading in watersheds will increase as stover removal rates are increased (Cibin et al., 2012). Studies have also shown some stover removal could actually reduce the amount of mineralizable N leaching off the fields, but over-removal could lead to a plant available nitrogen deficit and other environmental problems (Cibin et al., 2012; Khanal et al., 2014; Moebius-Clune et al., 2008). This reduction in nitrate leaching is due to the reduction in mineralizable N that may occur when stover is removed (Cibin et al., 2012; Khanal et al., 2014). Maize stover removal as a biomass source could also have long term negative environmental effects, with greater nutrient losses to surface waters (Osborne et al., 2014). Nitrogen balance in a system using maize stover for biofeedstock is driven by fertilizer application, and it has been shown that 30-75% of maize stover can be harvested safely to maintain this balance (Khanal et al., 2014). Osborne et al. (2014) determined that a lower level of residue removal resulted in a greater amount of large soil aggregates, which stabilize soil, help supply nutrients to plants, hold water, and prevent soil erosion. The same study also evaluated the effects of residue removal rates on erodibility of the soils, including effects from cover crops and fertilizer application. They found that with stover removal, erosion is likely to increase, however cover crops can temper the effect (Osborne et al., 2014). While there are other treatments for maize production that can affect soil health and erosion, stover removal rate had the greatest effect on soil erosion (Osborne et al., 2014)

2.1.2 Sorghum

In the Midwest sorghum can be viewed as a relatively low-risk transition crop for farmers interested in producing a dedicated bioenergy crop because the maize planting and harvesting equipment only need minor adjustments for sorghum (Espinosa and Kelley, 2014). Many Midwest farmers already grow sorghum or have grown it in the past, so the familiarity with it makes it more suitable for initial bioenergy crop growth. Sorghum originates in arid areas of north-east Africa (Rooney et al., 2007). In the US, sorghum is grown more often in the South and West instead of the Midwest, and the majority of the sorghum in the world is grown in Africa and Asia. Sorghum has potential as a bioenergy crop for reasons including: yield potential and composition, water-use efficiency and drought tolerance, salinity resistance, and potential for genetic improvements (Almodares and Hadi, 2009; Miller and McBee, 1993; Rooney et al., 2007). Thus, when compared to maize, it is adapted to a wider range of U.S. agroecozones (Almodares and Hadi, 2009; Miller and McBee, 1993; Rooney et al., 2007). Further, different varieties of sorghum can be chosen based upon the type of conversion pathway desired. Grain sorghums provide starch for conversion, sweet sorghums provide sugars, and cellulosic sorghums (high biomass) produce structural carbohydrates (lignin, cellulose, and hemi-cellulose) (Rooney et al., 2007).

When producing sorghum for biofuel conversion, there are multiple genetic traits that are more desirable based on the targeted conversion strategy. In reviews by Almodares and Hadi (2009) and Rooney et al. (2007), it is noted that these traits include: lignin content, mineral uptake and content, non-structural carbohydrate concentration and dhurrin levels. Sorghum cultivars with lower levels of lignin are more desirable in the conversion pathway because less methane is produced. However, these cultivars also tend to be a smaller size, yielding less raw material for conversion to energy (Miller and McBee, 1993). The genetic mutation known as brown mid-rib in sorghum results in a reduced level of lignin, and therefore vegetative tissues digest more completely in some conversion processes (Miller and McBee, 1993; Rooney et al., 2007). Despite these virtues of sorghum as a biofuel crop, some disadvantages and concerns with production may hinder its use. Because sorghum is not currently a high-value crop, such as maize or soybeans in the Midwest, it is not as advanced in research targeting crop improvement and management, in terms of best crop management practices. This, along with a continuous cropping system, can lead to weed control problems; and control is important to maintain as modification moves forward (Saballos, 2008; Zegada-Lizarazu and Monti, 2012). There are pre-emergence herbicides available for use with sorghum (Saballos, 2008). Due to the resilience of sorghum, pests and diseases are often not a serious problem (Saballos, 2008; Zegada-Lizarazu and Monti, 2012). However most varieties of sorghum are sensitive to organophosphorus pesticides, so other pest controls may be needed (Zegada-Lizarazu and Monti, 2012). Given annual bioenergy crops are expected to underperform on marginal lands, with or without fertilizer use, there is concern that pathogens and pests will become a greater threat (Reddy and Zehr, 2014). Overall, this potential for genetic modification to improve the crop for the conversion pathway and its ability for growth with less pesticides, herbicides and nutrients than annual crops in many regions of the U.S. are reasons sorghum is a viable crop for maize farmers to transition to for biofuel production.

2.2 Perennial grasses

As of 2006, just prior to the release of the EISA, the biofuel industry was not yet established and associated research not yet sufficiently complete for perennial grasses to garner as much attention as annual row crops (Ragauskas et al., 2006), but both have expanded since that time. Following the Ragauskas et al. (2006) review, a committee was created by the Water Science Technology Board to examine potential water quality effects of biofuel crop production. Studies evaluated by this committee have shown potential environmental advantages to perennial grasses as feedstock, including low nutrient use and low pesticide requirements (Committee on Water Implications of Biofuels Production in the United States, 2008). Perennial grasses also have the potential to contribute to soil, water, and nutrient conservation, and decreased runoff and chemical losses due to their extensive root system and extensive spatial and temporal aboveground coverage (Christian and Riche, 1998; Helmers et al., 2009; McIsaac et al., 2010). By definition, perennial grasses can be grown and harvested for multiple years without any replanting and associated soil disruption. The lack of soil disruption leads to increased soil organic matter and decreased soil erosion, thereby increasing soil water and nutrient retention (Borjesson, 1999; McLaughlin and Walsh, 1998). Hydrologic modeling of switchgrass and *Miscanthus* production has shown that production of these crops may reduce erosion when compared to maize, wheat and soybeans (Cibin et al., 2015; Thomas et al., 2014). Theoretically, perennial grasses have positive environmental effects partially due to lower fertilizer requirements and seasonal cycling of nutrients (Burks, 2013; Wedin and Tilman, 1990). The extensive and persistent root systems of perennial grasses have many benefits including efficient water and nutrient uptake and more stability during stress years (McLaughlin and Walsh, 1998). These root systems also reach much deeper than annual crop root systems and permit greater access to water and nutrient resources (Burk, 2013; Neukirchen et al., 1999). A recent study suggests that, even during their establishment phases, annual NO_3-N losses from unfertilized *Miscanthus* and switchgrass are very similar and much lower than from maize (Lesur et al., 2014). It is important to note, however, that, even with all of these benefits, there could be some disadvantages to growing perennial crops for biofuel production. These disadvantages can include low yields during the establishment phase.

Miscanthus is more widely grown and studied in Europe, where it has been shown to produce high yields, while switchgrass has often been the focus in the U.S. where it is native (Heaton et al., 2008). Prior to 2008 there were no peer-reviewed articles available presenting results from rigorous side-by-side comparisons of *Miscanthus* and switchgrass. Since the culmination of the study reported here, two such comparisons have been completed, but both were conducted on prime agricultural land; comparative outcomes on marginal lands remain undocumented (Trybula, 2012, McIsaac et al., 2010). Those studies moved forward the knowledge-base of these crops, but not fill the knowledge gap regarding perennial grasses grown on marginal lands.

2.2.1 *Miscanthus*

Although originally studied more widely in European countries (Lesur et al., 2014; Lewandowski et al., 2000), some studies of *Miscanthus* have begun at American universities, such as the University of Illinois (Heaton et al., 2008). *Miscanthus* is a perennial, warm-season grass, and the species *Miscanthus x giganteus* is a sterile hybrid that, at present, must be established by rhizome planting (Lewandowski et al., 2000). *Miscanthus* has the advantage of higher yields, up to 20-30 t ha^{-1} dry matter, as compared to 12 t ha^{-1} total dry matter (grain and 51% stover removal) from maize (Burks, 2013; Heaton et al., 2008; Varvel et al., 2008) and around 8-26 t ha^{-1} dry matter from switchgrass (Burks, 2013; Heaton et al., 2008; Lesur et al., 2014; Lewandowski et al., 2000). *Miscanthus* also has lower fertilizer inputs than traditional row crops, typically 60 kg N ha^{-1} (Lesur et al., 2014; Lewandowski et al., 2000), compared to 100-200 kg N ha^{-1} for maize (Vitosh et al., 2000). The lower fertilizer requirements are expected to lead to lower nutrient losses to surface and subsurface waters. Burks (2013) found an establishing stand could accumulate up to 14 Mg dry matter ha^{-1} in rhizomes. By doing that, *Miscanthus* can store nitrogen below the surface for use in early spring growth, again allowing for lower fertilizer requirements (Neukirchen, et al., 1999). In an establishment-phase field study by Lesur et al. (2014), NO_3-N leaching to subsurface water was determined to be very low, although leaching losses in the first winter (11 kg N ha^{-1}) were higher than in the second winter (2 kg N ha^{-1}); an expected result given that the crops are not yet established and therefore did not reach their potential growth.

This study as well as others used a hydrological model that estimated replacing maize-soybean rotations with *Miscanthus* would reduce the NO_3-N loading in a watershed (Lesur et al., 2014; Thomas et al., 2014; Trybula, 2012). These simulation studies are further supported by the fact that *Miscanthus* can continue to take up nutrients from soil into the fall (Lesur et al., 2014). Some potential disadvantages to the use of *Miscanthus* as a biofuel crop have been identified and include decreased soil moisture and low winter hardiness (McIsaac et al., 2010). For example, McIsaac et al. (2010) found that *Miscanthus* reduced soil moisture throughout the growing season when compared with either maize-soybean or switchgrass, which could impact the water cycle by increasing the low flow season of nearby creeks and rivers while soil moisture levels recharge. The crop is also sensitive to low temperatures and has poor winter hardiness during extreme weather, especially during the establishment years (Lewandowski et al., 2000). Another disadvantage to *Miscanthus* is that it must be established by transplanting rhizomes, which is time consuming and currently done by hand (McIsaac et al., 2010). *Miscanthus* has a narrow genetic base in the field because it is vegetatively propagated through rhizomes which means each plant is a genetic clone. A narrow genetic base can lead to susceptibility to catastrophic stand losses when adverse conditions prevail, as the response will be uniform across the crop system (Lewandowski et al., 2000). While these disadvantages should be further investigated, many prime agricultural land studies (Lesur et al., 2014; Lewandowski et al., 2000; McIsaac et al., 2010) have demonstrated that *Miscanthus* has advantages that may help to meet the EISA goal for biofuel production while having minimal impact on water quality.

2.2.2 Switchgrass

Switchgrass is a prairie grass native to regions of North America. After a succession of trials, the U.S. DOE chose switchgrass to be one of the main focuses of further biofuel studies due to switchgrass the broad adaptation throughout the U.S., high yields on marginal lands, and its ability to be harvested using conventional hay-harvesting equipment (Vogel et al., 2002, Wu and Liu, 2012). The upland ecotype of switchgrass is found mostly in drier soils and northern climates, while the lowland ecotype is found more often in wetter soils and southern climates (Stroup et al., 2003; Wullschleger et al., 2010). Lowland cultivars have demonstrated ability to adjust to adverse environmental conditions and produce higher yields than upland types (Alexopoulou et al., 2008; Stroup et al., 2003). Liberty switchgrass is a high-yielding, lowland cultivar bred at the University of Nebraska-Lincoln. It is the product of two cultivars, Summer and Kanlow, and is bred in part to survive the harsh Midwest winters like an upland ecotype while maintaining superior yields (Vogel et al., 2014).

Switchgrass has stiff, upright stems, and grows very densely. This, along with its extensive root system, slows water runoff and allows nutrients and soil to settle out of the water instead of running off, a potential benefit on marginal lands (Meyer, et al., 1995). Switchgrass has been shown to produce a large amount of small roots, in contrast to *Miscanthus* producing mostly rhizomes. It can produce around 5.2 Mg ha^{-1} of rhizomes and 5.5 Mg ha^{-1} of small roots (Burks, 2013). McLaughlin and Walsh (1998) noted that switchgrass has high water use efficiency, giving it the ability to keep producing even in summer months when water becomes more scarce. Furthermore, a more recent review by Domiguez-Faus et al. (2009) noted that switchgrass has a lower N requirement thereby reducing fertilizer losses to surface waters. The years of experience growing switchgrass as a forage or hay crop has led to a large knowledge-base demonstrating switchgrass' ability to be productive on rain-fed, marginal lands (Mitchell et al., 2008). In a study on marginal land at the University of Nebraska, switchgrass was shown to have the same or greater potential ethanol yield as maize grain and stover (Varvel et al., 2008). Natural adaptation coupled with recent crop improvement efforts suggest switchgrass may be more competitive with *Miscanthus* in terms of biomass production while retaining advantageous ecosystem services associated with native crops and reducing concern for invasive take-over (Mitchell et al., 2008).

2.3 Short-rotation woody crops (SRWC)

Many poplar species are native to the Northern Hemisphere and the United States, and breeders have developed a hybrid suitable for bioenergy production. Because of perceived importance in feedstock conversion, the focus of genetic modifications has been on the density of the wood and on lignin and cellulose composition (Sannigrahi et al., 2010). Common poplar species, upon maturity, can grow to approximately 26 m in height with trunk diameters of 60 cm (Sannigrahi et al., 2010), however this is a much longer time than poplar stands are expected to grow prior to harvest. A suggested practice for poplars grown for biomass is to harvest every 3 years, with stands being viable for 25-30 years and an anticipated yield between 7 and 12 t ha^{-1} (Rowe et al., 2009). Poplar stands may be able to grow without fertilizer input, reducing nitrate leaching when compared to traditional crops. However, it is likely that commercial SRWC will be fertilized to maintain maximum yield (Rowe et al., 2009). Poplars can provide extensive ground cover, roots, and increased interception of stormwater, therefore reducing erosion risk (Rowe et al., 2009). Using short rotation poplar has the potential to also increase ecosystem benefits and biodiversity such as increased flora and avian diversity (Gasol et al., 2009; Ledin, 1998; Rowe et al., 2009). One significant disadvantage to poplar and SRWC is the comparatively high water demand, which is expected to constrain production to areas with either ample rainfall or access to supplemental irrigation. This is, in part, due to higher transpiration rates for SRWC, which can average 6 mm day^{-1} as compared to 2.3 mm day^{-1} for *Miscanthus* (Rowe et al., 2009). This water demand can also have an effect on the local hydrology by potentially lessening flow to groundwater or local streams, further limiting where this crop can be suitably grown (Gasol et al., 2009).

A few studies have evaluated the environmental effects of replacing crop land with SRWC (Dominguez-Faus et al., 2009; Perry et al., 2001; Updegraff et al., 2004). These studies use computer modeling and assume crops will be produced on prime farmland. These models indicate a positive environmental effect of growing SRWC in place of traditional crops, including a reduction in runoff (up to 29%), erosion (up to 65%), and nitrogen loading in runoff (up to 35%), but with an increase in phosphorus loading in runoff (up to 29%) (Updegraff et al., 2004).

CHAPTER 3. METHODS

3.1 Study Area

The study area was located at Throckmorton Purdue Agricultural Center (TPAC) in Lafayette, IN; latitude 41°17'45, longitude -86°54'13 (Figure 3.1). During the study period, January 2013-November 2014, the average high and low temperatures were 34.2°C and -23.1°C, respectively; annual precipitation averaged 95.1 cm. Over the previous years (2004-2012), the average high and low temperatures were 34.4°C and -22.6°C, respectively; the average annual precipitation was 103.4 cm. There were two experimental sites located within TPAC. These are designated TPAC West and TPAC East and are described in greater detail below.

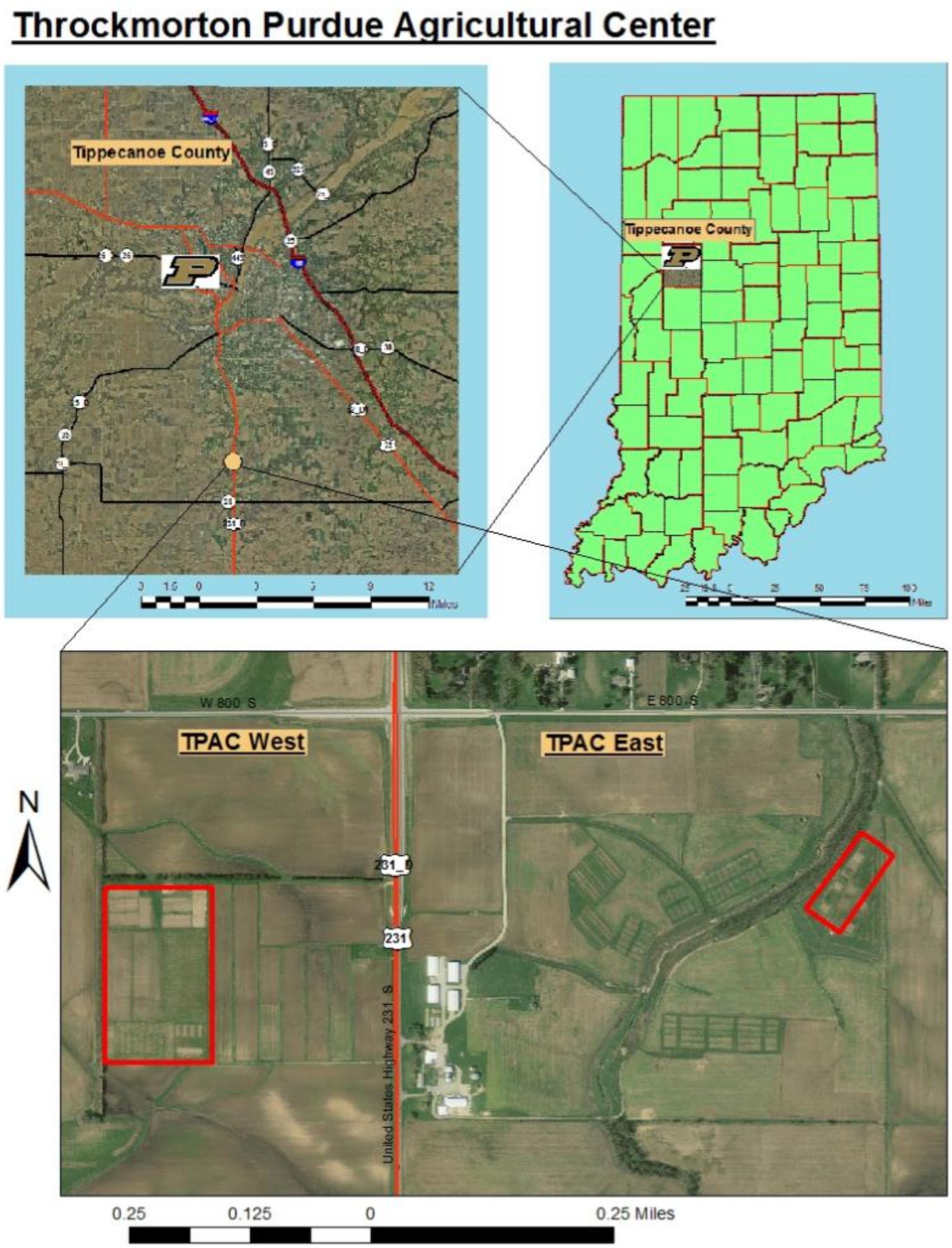


Figure 3.1 Throckmorton Purdue Agricultural Center (TPAC). Location within Tippecanoe Co., IN. Both sites, TPAC West and TPAC East are designated.

3.2 TPAC West

At TPAC West, there were four plant nutrition/soil fertility studies for candidate bioenergy crops already ongoing. For the work reported here, a leachate monitoring study was superimposed on these existing studies by equipping selected plots for subsurface water sampling (Figure 3.2). The soils in the plots were mostly silt loam; the soil series were Toronto (fine-silty, mixed, superactive, mesic Udollic Epiaqualfs), Octagon (fine-loamy, mixed, active, mesic Mollic Oxyaquic Hapludalfs), Lauramie (fine-loamy, mixed, active, mesic Mollic Hapludalfs), and Drummer (fine-silty, mixed, superactive, mesic Typic Endoaquolls). These soils were classified as eroded with 2-6% slopes and generally low in soil fertility according to regional soil testing recommendations (Vitosh et al, 1995) and can thus be considered marginal for annual row-crop production (Milbrandt et al., 2014). Leachate samples were collected from spring 2013 through the fall harvest of 2014 using a suction cup lysimeter (Soil Moisture soil water samplers 1900L12) inserted to a depth of approximately 30 cm. The four ongoing experiments used in this study were nutrient trials with switchgrass, *Miscanthus*, native prairie, and sorghum and maize (Figure 3.2).

The “Shawnee” switchgrass plots were planted in 2007 (Figures 3.2 and 3.3). Prior to that, the experimental area was planted with alfalfa (1997 to 2006) followed by one year of maize production (2006). “Shawnee” switchgrass was no-till drilled into corn stubble. The switchgrass was seeded at a rate of 6.7 kg ha^{-1}. The historic alfalfa P/K experiment had four treatments arranged in a random complete block design with four replicates. The P/K treatments applied were 0/0, 0/400, 75/0, and 75/400 kg ha^{-1} yr^{-1} P and K, respectively. Applications occurred annually from 2001 to 2004, inclusive (Berg et al., 2009). The on-going switchgrass bioenergy experiment overlaid the historic plot with an N rate experiment where 4 rates of N (0, 50, 100, 150 kg ha^{-1} yr^{-1}) are applied annually as a randomly assigned split-plot treatment within the P/K main plots. Individual N rate subplots measured 3 x 9 m. For the leachate monitoring work reported here, we chose only two of the four historic P/K treatments (0,0 and 75,400 kg P,K ha^{-1} yr^{-1}). The historical P and K rates led to this site having higher residual P and K soil levels in half of the plots (Table 3.1).

The *Miscanthus* experiment (Figures 3.2 and 3.3) was established in Spring 2009 by hand-transplanting plants propagated from rhizomes, at 1 per square meter, for a total plot size of 4 x 10 m. The previous crops for this experiment were alfalfa (1997-2005), maize (2006) and switchgrass (2007-2008). The switchgrass was tilled under spring 2009, prior to the planting of *Miscanthus*. The *Miscanthus* plots (Figure 3.3) were planted in a randomized complete block split plot design with four replicates and a main treatment of four N rates (0, 50, 100, 150 kg ha^{-1} yr^{-1}), and two subplot treatments: without P and K or with P and K added at 30 kg ha^{-1} yr^{-1} and 300 kg ha^{-1} yr^{-1}, respectively.

The last perennial experiment used in the leachate study was a comparison of *Miscanthus* and Liberty switchgrass with mixed species stands of native prairie grasses grown without supplemental fertilizer; these plot were 6 x 9 m (Figures 3.2 and 3.4). The plots were established in 2011 following a cropping history of alfalfa (2000-2005), soybeans (tilled, 2006), maize (no-tilled, 2007), soybeans (no-tilled, 2008), wheat (tilled, winter of 2008-2009), and soybeans (tilled, 2009-2010). Following tillage, the mixed prairie was planted in 2011 by hand broadcasting seed (4.5 kg ha^{-1}, each of indiangrass and big bluestem) and finishing with a culti-packer. Within the ongoing prairie comparative experiment, only the four replicates of mixed native prairie plots were selected for this study.

Prior to the 2011 implementation of the annual maize/sorghum experiment (Figures 3.2 and 3.4), the cropping history for the land area was as described for the mixed prairie plots (above). The annual plots were arranged in a 4x5 factorial split plot design (Figure 3.4) with four replicates and plots sized 4.5 x 6 m. The main plot treatments included five N rates (0, 50, 100, 150, 200 kg ha^{-1} yr^{-1}). Subplots were four annual crops (dual purpose sorghum, photoperiod sensitive sorghum, sweet sorghum and maize) randomly assigned as split plots within main plot treatments. For this leachate monitoring study, we selected only the dual purpose sorghum and maize (control) with the N rates of 0 and 150 kg N ha^{-1}.

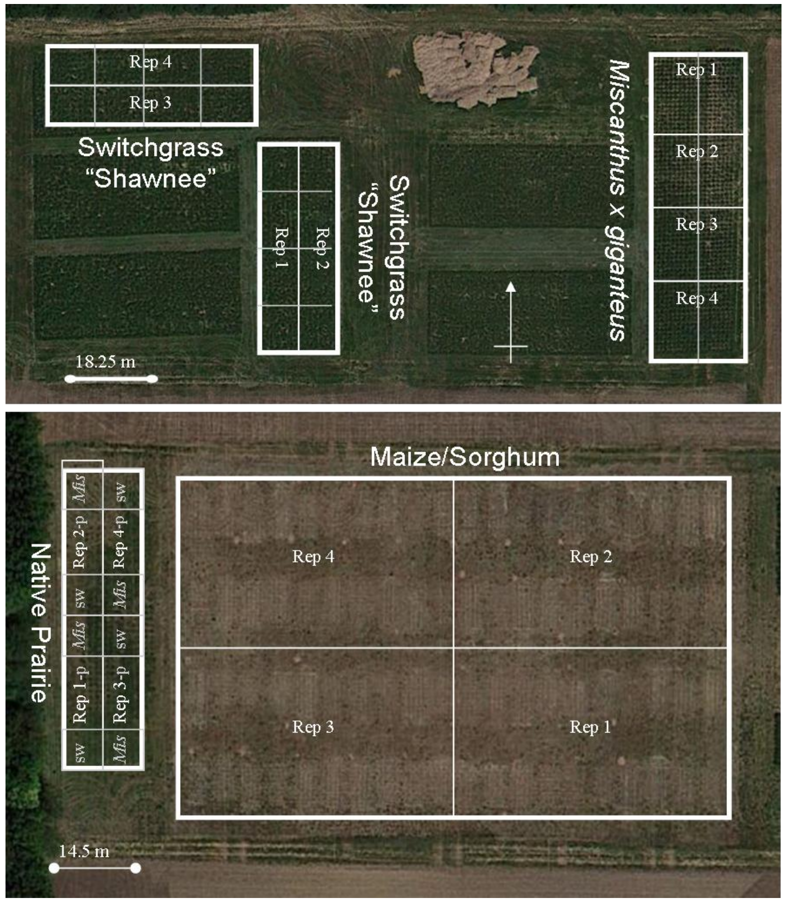


Figure 3.3 Randomized complete block split-plot layout of the TPAC West experiments including separate experiments for *Miscanthus*, switchgrass, sorghum, maize and native prairie. Each experiment has four replicates.

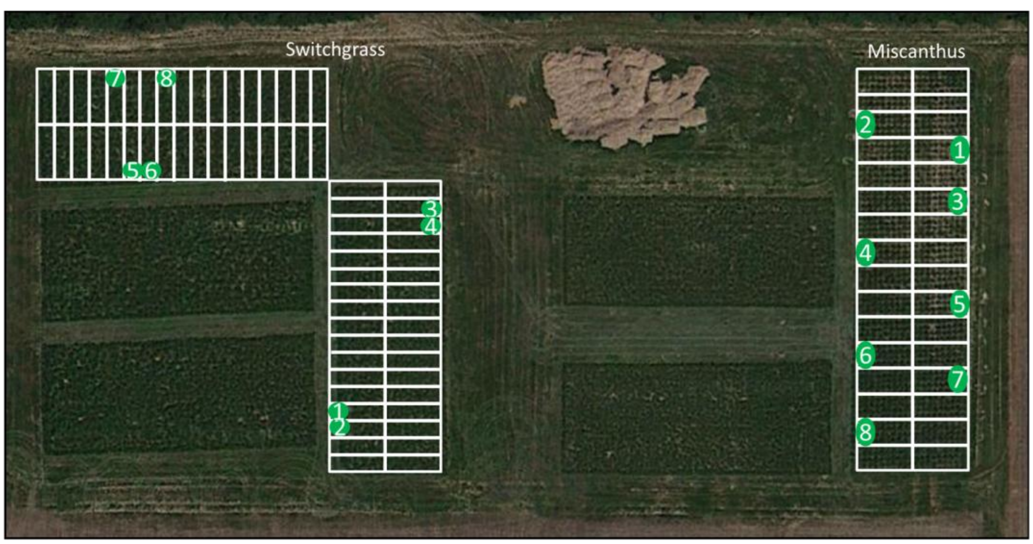


Figure 3.2 TPAC West perennial grass experiments; locations of lysimeters are shown and numbered sequentially by replicate (e.g. replicate 1, lysimeter 1 & 2).

3.2.1 TPAC West Field Management

All experiments were rain fed and no tillage was used to manage residue. The seeding rates for maize and sorghum were set at 79,040 and 269,230 seeds ha^{-1}, respectively. Maize and sorghum were planted in early June (6/7/13, 6/7/14) using a John Deere 7200 MaxEmerge2. Annual fertilizer applications were made once in May (5/7/13, 5/6/14) for the perennials and in late June (6/27/13, 7/2/14) for the annual row crops. The N fertilizer was Agrotaine-coated urea for the *Miscanthus* and switchgrass plots, broadcast applied, and urea ammonium nitrate (UAN, 28%), knifed in, for sorghum and maize plots. The P fertilizer applied to *Miscanthus* plots was super triple phosphate (0-46-0; P_2O_5). The K fertilizer applied to the *Miscanthus* and switchgrass plots was a muriate of potash (0-0-60; KCl). Both P and K fertilizers were broadcast applied. The annuals are also treated with pre-emergent herbicides (glyphosate, ammonium sulfate, atrazine, and crop oil). *Miscanthus*, switchgrass, maize, and sorghum were harvested after first frost in late October-November. During this study, *Miscanthus* was harvested 10/28/13 and 12/10/14, switchgrass 10/28/13 and 12/3/14, and maize/sorghum 10/28/13 and 12/1/14. These plots were harvested using a CIBUS-S Wintersteiger with a Kemper silage head forage chopper. Harvest samples were collected using a Harvestmaster. Subsamples were dried in a forced air oven at 60^{o}C and percent dry weight was calculated using Equation 1.

$$\text{Equation 1: } \%\, DW = \frac{subsample\ wt\ (g) dried}{subsample\ wt\ (g) wet}$$

Total harvest dry matter weight was calculated using a total harvest weight and the percent DW calculated from the subsample. Yield was calculated using length and width of the harvester passes to measure area and total harvest dry matter weight (Equation 2).

Equation 2: $Yield = \frac{total\ DM\ (kg)}{harvested\ area\ (ha)}$

Prior to machine harvesting of sorghum and maize plots, a 10-plant subsample was harvested by hand, cutting close to the soil surface. These subsamples were partitioned into grain and stover and dried to constant weight. Because they were removed from the rows that were then harvested with the Wintersteiger, the 10-plant dry weight was then added back to the dry weight of machine harvested yields.

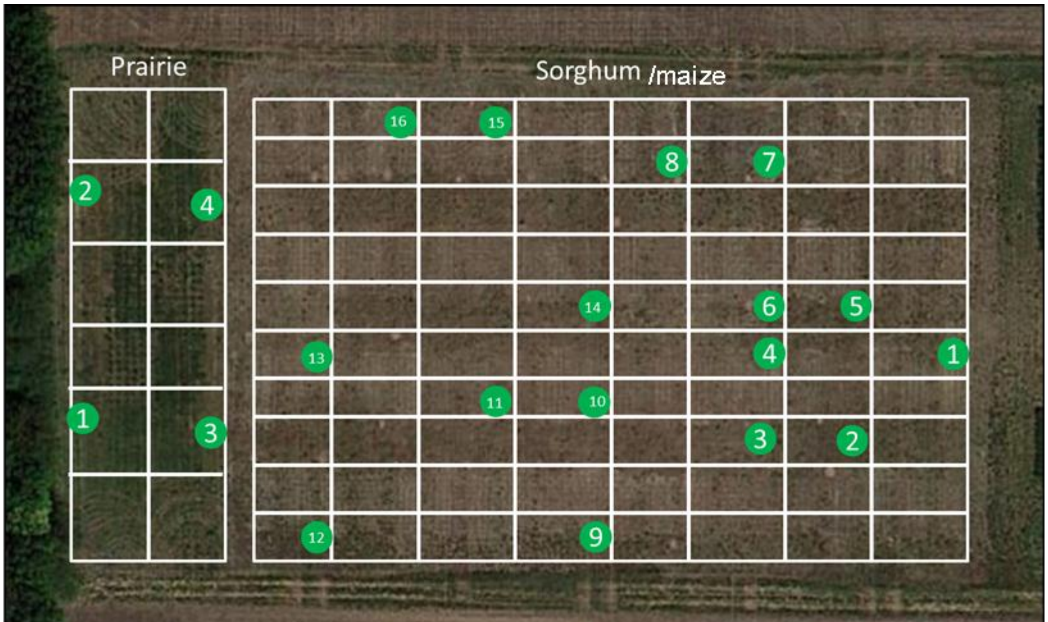


Figure 3.4 TPAC west annual row plots and native prairie plots with green dots to indicate subsurface lysimeter sampling.

Table 3.1 Soil test values measured in the experimental main plots of the Shawnee switchgrass (Figure 3.2). Values shown for 0-10 and 10-20 cm depth increments are means of four replicates.

	Switchgrass soil test values		
Historic P/K Treatments*	Soil depth (cm)	Phosphorus (P-M3^) (μg/g)	Potassium (K-M3^) (μg/g)
0/0 kg ha^{-1}yr^{-1}	0-10	6.4	110.5
	10-20	4.14	91.4
75/400 kg ha^{-1}yr^{-1}	0-10	10.8	137.2
	10-20	3.5	90.7

^M3 refers to Mehlich 3 extraction method for soil testing. Mehlich (1984)

3.3 TPAC East

An additional experiment was located on the east side of TPAC. This site was selected because it was on a sloping land (6-12%) and highly erodible (Figure 3.5). The soils at this location are characterized as Octagon (fine-loamy, mixed, active, mesic Mollic Oxyaquic Hapludalfs) that have been overlaid with soil removed during the building of a nearby road. Prior to the establishment of the experiment, the land was planted to a maize and soybean rotation using zero tillage. The experiment features five crops: *Miscanthus x giganteus*, Liberty switchgrass, dual purpose sorghum, and hybrid poplars (*Populus alba*), with maize grown as a control. Crops are grown in a randomized complete block design with 4 replicates; each plot is 13m x15m. These plots were established in May 2011, and measurements for this experiment were collected from January 2013 to November 2014. One replicate of the study site was set up for water quality and quantity monitoring (Figure 3.6). Plots within this replicate were separated by metal plates (15m in length) vertically inserted in the soil to prevent any overland water flow between adjacent plots. Ground berms running across the top and bottom of the replicate prevented the run-on and uncontrolled runoff of water into the plots. The flow of water across the plot was funneled into metal flumes, located in the north corners, which directed all water into large collection tanks. Located inside the tanks was a Solinst Levelogger model 3001 to quantify the volume of runoff water. All plots equipped with flumes also contained three suction cup lysimeters for subsurface water sampling. Lysimeters were located in a diagonal downhill pattern from the southeast corner to the north corner with each lysimeter inserted to a depth of approximately 30 cm. The center of each plot also housed soil moisture sensors (Campbell Scientific CS655) located at three different depths (10, 20, and 30 cm). A weather station was also located next to these plots that collected data on: precipitation, air temperature, wind speed, relative humidity, and solar radiation. Soils were sampled in 2012 and sent to A & L Great Lakes laboratory for analysis of phosphorus, potassium, magnesium, calcium, soil pH, cation exchange capacity. Results from soil phosphorus testing done prior to the start of this experiment are shown in Table 4.6 and Appendix C.

Figure 3.5 Randomized design of all four replicates of biofuel crops at TPAC east.

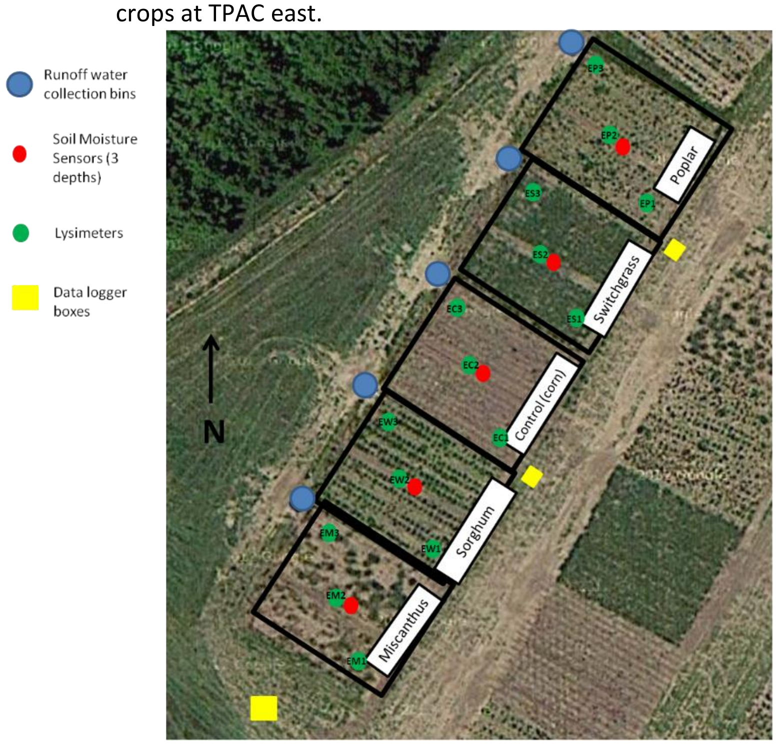
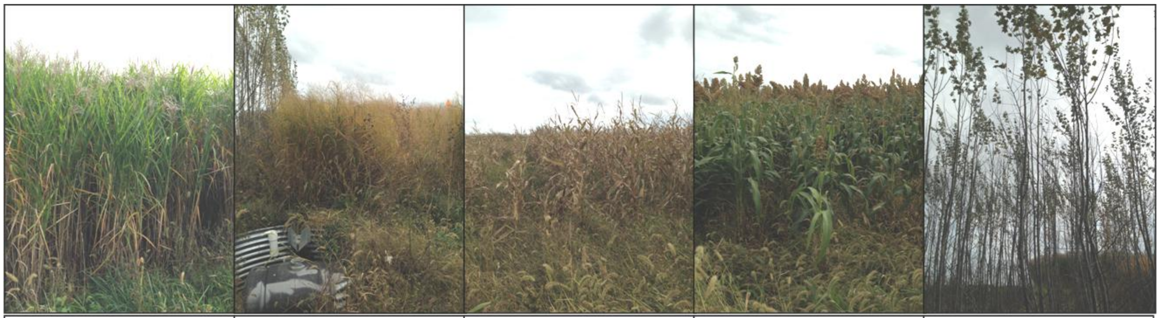


Figure 3.6 Water quality and quantity sampling setup at TPAC east, replicate one.

3.3.1 TPAC East Field Management

In general, crop management for TPAC East followed best management practices for fertilizer rates (Figure 3.7) (Cadoux et al., 2012; Miguez et al., 2008; Muir et al., 2001; Vitosh et al. 2000; Vogel et al., 2002) . Seeding rates, planting and tillage practices were the same as described for TPAC West. Annuals were planted 6/7/13 and 6/7/14. Perennial grasses received 50 kg N ha^{-1} of Agrotaine-coated Urea on 5/14/13 and 5/6/14, while the annual row crops received 150 kg N ha^{-1} urea ammonium nitrate (UAN 28%) on 6/27/13 and 6/23/14. The poplar tree plots did not receive any fertilizer. Due to equipment limitations, the Agrotaine-coated Urea was broadcast by hand on these plots, and the UAN was knifed in as described for TPAC West. *Miscanthus*, switchgrass, maize, and sorghum were then harvested on 11/25/13 and 12/10/14, after frost. These plots were harvested as described for TPAC West. In 2013, Rep 1 (equipped for water quality sampling), was hand-harvested using a walk-behind sickle mower and hand collecting all aboveground biomass. This was due to equipment limitations with the harvester on steeply sloping ground. Biomass yields were calculated as described for TPAC West.



Miscanthus x giganteus	"Liberty" switchgrass	Maize	Dual-Purpose Sorghum	Poplar
50 kg/ha Agrotaine-coated Urea		150 kg/ha Urea Ammonium Nitrate (UAN, 28%)		No fertilizer

Figure 3.7 TPAC East, all crops and fertilizer treatments. Pictures taken at field site, October 2014.

3.4 Sample Collection

Surface runoff samples were collected following every major storm event. Over the study period, there were 21 storm events and 86 lysimeter collection dates, resulting in 74 and 996 surface and subsurface samples, respectively; these occurred between spring 2013 and the fall harvest of 2014. To collect runoff water samples, the tanks were shaken to make sure the samples were well-mixed and 500 mL of water were collected from each tank per sampling visit. Event runoff volume was calculated using Leveloggers. The runoff collection tanks were emptied after each collection to preserve the integrity of runoff volume measurements and quality of samples from the next event. After rainfall events, an aliquot of the runoff collected from each tank was analyzed for nutrient content (described below), and nutrient loads were calculated as follows:

Equation 3: $volume\ (L) * concentration \frac{mg}{L} * \frac{1}{0.02\ ha} = load\ \frac{mg}{ha}$

where volume is the total volume recorded for each storm event, concentration is nutrient concentration measured from the aliquot collected, and 0.02 ha is the area of each plot. Sub-surface lysimeter samples were collected with varying frequency. During the wettest months of April and May (Appendix A), samples were collected three times per week. As the weather got warmer and rain events decreased, sampling decreased to twice a week, followed by once per week until harvest (Appendix B). Subsurface sampling did not occur in the winter due to extremely cold conditions. Subsurface samples were collected using long plastic tubing and a 60 mL syringe. The tubing was fed into the lysimeter until it rested on the bottom and then the syringe was used to extract the sample. The syringe was rinsed with water between sequential samplings. Samples ranged anywhere from 5-250 mL in volume, with just one sample saved per lysimeter per visit.

3.5 Analysis

3.5.1 Laboratory Analysis

Subsurface samples were analyzed for NO_3-N and soluble reactive phosphorus (SRP). Surface samples were analyzed for NO_3-N, SRP, total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). Nutrient analyses for samples were completed with a Seal AQ2 Auto Analyzer ©. The NO_3-N (NO_x) test protocol was method no: EPA-114-A Rev. 9, equivalent to USEPA Method 353.2. This method was a colorimetric test using a cadmium coil to reduce nitrate to nitrite and a sulfanilaminde and N-(1-naphthyl)-ethylenediamine dihydrochloride reagent to detect nitrite. The SRP (o-PO_4) test was AQ2 method: EPA-118-A Rev. 5, equivalent to USEPA Method 365.1. The TP samples were digested and analyzed with method: EPA-199-A Rev. 7, equivalent to USEPA 365.1. These tests used an ammonium molybdate and antimony potassium tartrate reagent to react with ascorbic acid to form a blue color that can then be detected with colorimetric analysis. The TN samples were digested following the Water-Resources Investigations Report 03-4174 and analyzed with AQ2 method for NO_3-N. The TSS were analyzed using EPA method 160.2. This method filters a known volume of sample through a fiberglass filter, using a vacuum, and the amount of solids left on the filter were then dried overnight at 105^{o}C and weighed to determine the TSS.

3.5.2 Statistical Analysis

TPAC West plots were distinguished by crops and fertilizer rate, and TPAC East plots were distinguished only by crop. Because TPAC East had only one replicate equipped with water quality sampling equipment, the three lysimeters located within each plot were treated as pseudo-replicates for the study. Subsurface water quality data was analyzed using an analysis of covariance (ANCOVA) (R, version 3.1.1) to test the main and interaction effects of the factors while controlling for the effects of the covariate. The independent variable was the pollutant (NO_x, o-PO_4, TN, TP, TSS) or yield and the factors were crop, fertilizer (high, low; only applies to TPAC West), and season. A Tukey's HSD test was used to determine factor significance. Because surface water samples have only one replicate, they were statistically examined as a comparison of means of multiple populations. This was done using R statistical package and a simple ANOVA test with crop as the only factor; a Tukey's HSD test determined factor significance. Linear regressions were done using Microsoft Excel.

CHAPTER 4. RESULTS & DISCUSSION

4.1 Results

4.1.1 Nutrient leachate concentrations in subsurface waters

4.1.1.1 Nitrate-N

At TPAC West, significantly greater concentrations of NO_3-N to subsurface waters (p<0.05) occurred in the maize and sorghum treatment receiving 150 kg N ha^{-1} (maize-high and sorghum-high) when compared to maize and sorghum plots with zero N applied. Subsurface NO_3-N concentrations of the perennial bioenergy crops ranged in average from 0.52 mg L^{-1} N to 4.3 mg L^{-1} N and were not significantly different, regardless of fertilizer treatment. The perennial treatments and zero N maize/sorghum treatments were not significantly different. The maximum concentrations of NO_3-N for high-fertilized maize and sorghum were two-fold or more (220.8 mg L^{-1} N and 176.9 mg L^{-1} N) than the maximums observed for the other crops and treatments (Table 4.1).

At TPAC East, most crop treatments were associated with a wide range of NO_3-N concentrations, but sorghum was the only crop with a statistically higher mean (p<0.05). Sorghum's maximum nitrate concentration (233.5 mg L^{-1} N) was almost three-fold the maximum concentration in maize (87.5 mg L^{-1} N), and more than three-fold that observed in all other crops (Table 4.2).

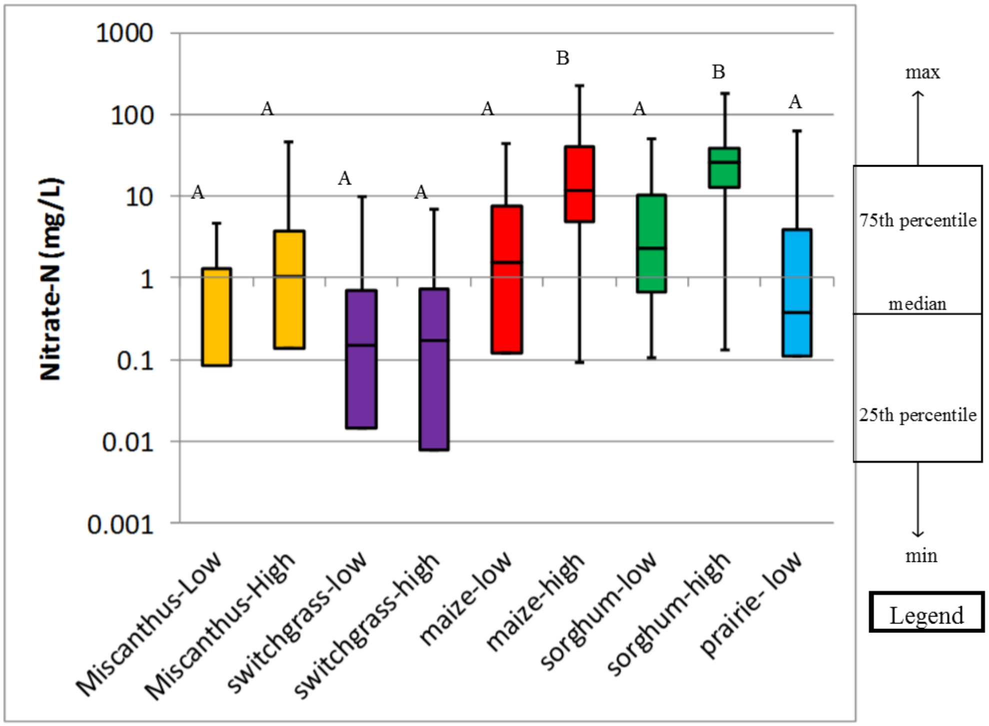


Figure 4.1 Effects of fertilizer rate and crop on NO_3-N concentration in lysimeter leachate measured at TPAC West. Crops labeled 'A' or 'B' have been found to have sample means that are significantly different (Tukey's HSD, p<0.05).Data shown include all samples from all replicates

Table 4.1 Mean and maximum concentrations of nitrate in TPAC west plots.

Crop	Mean concentration (mg/L)	Max concentration (mg/L)	Number of samples (N)
Miscanthus-low	0.74	4.6	86
Miscanthus-high	4.3	45.9	96
switchgrass-low	0.52	9.8	120
switchgrass-high	0.61	6.8	139
maize-low	5.9	43.3	34
maize-high	36	220.8	34
sorghum-low	7.6	49.5	30
sorghum-high	37.2	176.9	33
prairie– low	2.7	63.7	105

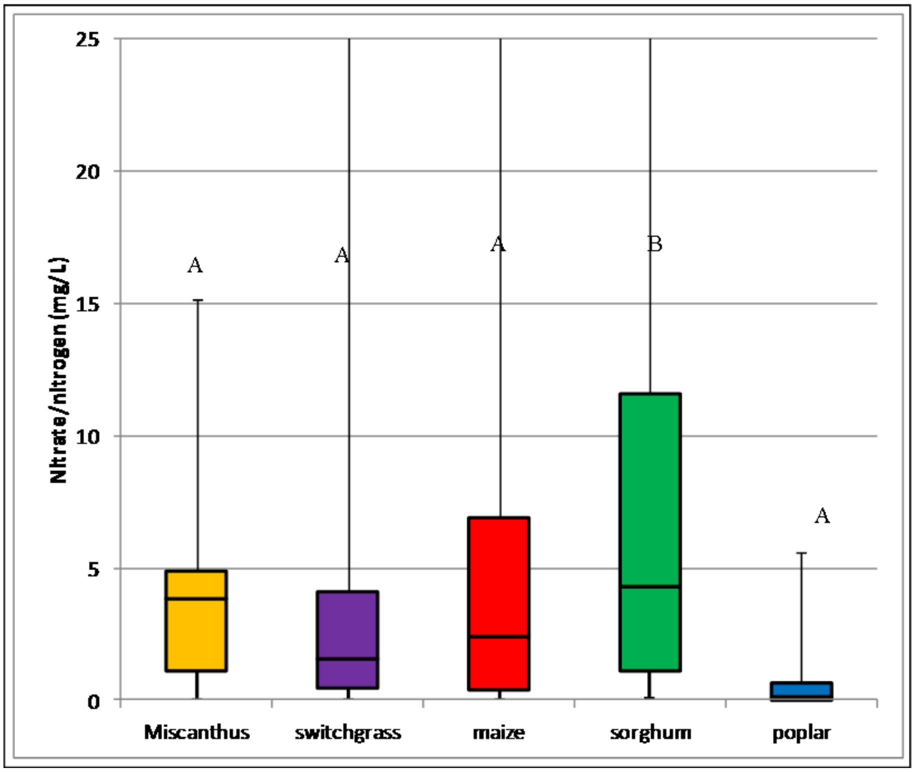


Figure 4.2 Effects of crop on subsurface NO_3-N concentration in leachate measured at TPAC East plots. Crops labeled 'A' or 'B' have been found to have sample means that are significantly different (Tukey's HSD, $p<0.05$). Data shown are from all samples in the three pseudo-replicates per plot.

Table 4.2 Mean and maximum concentrations of nitrate measured in TPAC East lysimeter samples.

Crop	Mean concentration (mg/L)	Max concentration (mg/L)	Numbers of samples (N)
Miscanthus	3.89	15.2	53
switchgrass	4.02	32.0	89
maize	7.28	87.5	56
sorghum	20.5	233.5	50
poplar	0.74	5.56	66

4.1.1.2 Soluble reactive phosphorus

At TPAC West, no significant differences (p<0.05) among all crops and treatments were found in the SRP concentration in lysimeter leachate (Figure 4.3). Maximum SRP concentrations ranged from a high of 4.6 mg L^{-1} in the prairie treatment to 0.81 mg L^{-1} in the *Miscanthus* zero P treatment (Table 4.3).

Although no crops are treated with phosphorus fertilizer at TPAC East, switchgrass and poplar showed statistically (p<0.05) lower SRP concentrations in leachate when compared to maize and sorghum (Figure 4.4). *Miscanthus* SRP concentrations fell in the middle range and the mean SRP was not statistically different from concentrations in other crops. The SRP maximum concentrations ranged from 0.96 mg L^{-1} in poplar treatment to 3.03 mg L^{-1} in sorghum treatment.

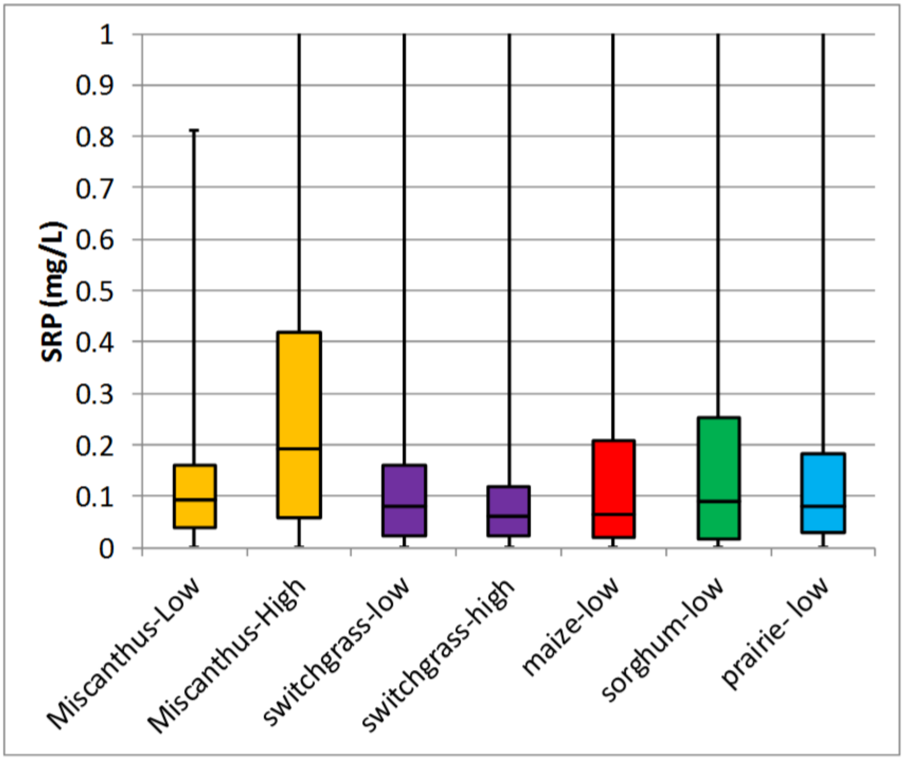


Figure 4.3 Effects of fertilizer rate and crop on SRP concentrations measure in lysimeters at TPAC West. No one treatment is significantly different from the others. Data shown are from all samples and replicates.

Table 4.3 Mean and maximum concentrations of SRP measured in lysimeters at TPAC West.

Crop	Mean concentration (mg/L)	Max concentration (mg/L)	Number of samples (N)
Miscanthus-low	0.12	0.81	86
Miscanthus-high	0.33	2.34	96
switchgrass-low	0.13	1.34	120
switchgrass-high	0.1	1.76	139
maize-low	0.9	1.10	34
maize-high	NA	NA	34
sorghum-low	0.18	1.92	30
sorghum-high	NA	NA	33
prairie– low	0.21	4.62	105

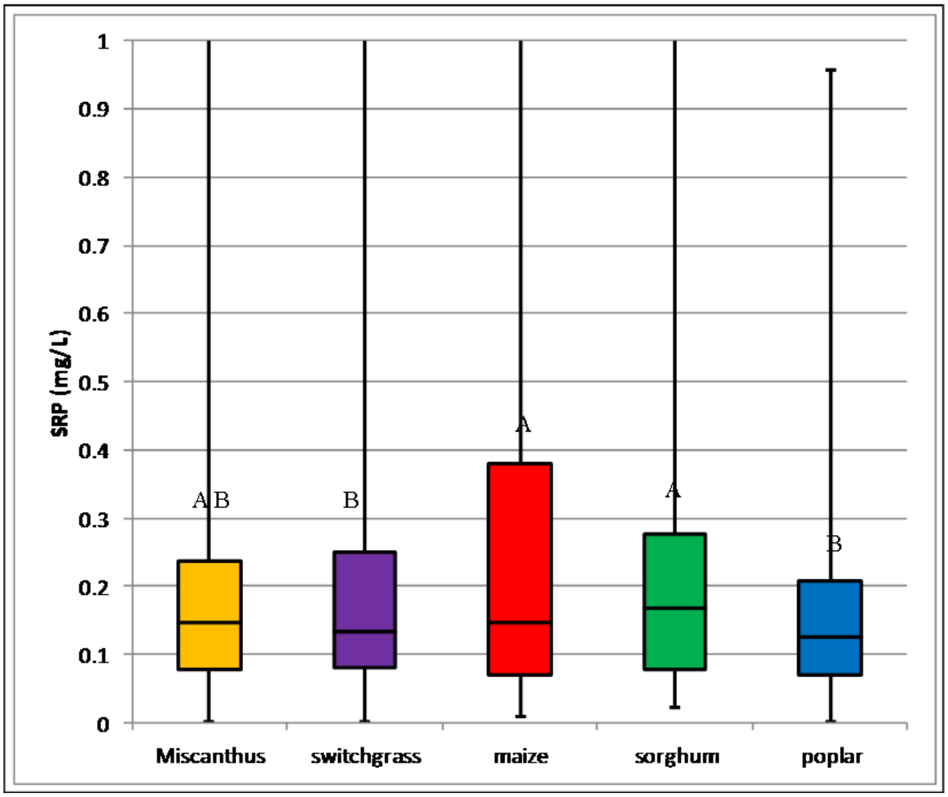


Figure 4.4 Effects of crop treatment on subsurface SRP concentrations in lysimeters at TPAC East. These plots receive no P fertilizer. Crops labeled 'A' or 'B' have been found to have sample means that are significantly different (Tukey's HSD, $p<0.05$). *Miscanthus* is not significantly different from any other treatment. Data shown are for all samples from all plots.

Table 4.4 Mean and maximum concentrations of SRP measured in lysimeter samples from TPAC East.

Crop	Mean concentration (mg/L)	Max concentration (mg/L)	Number of samples (N)
Miscanthus	0.24	1.31	53
switchgrass	0.19	1.2	89
maize	0.40	2.88	56
sorghum	0.36	3.03	50
poplar	0.16	0.96	66

4.1.2 Nutrient losses to surface runoff

Figures 4.5-4.10 show 2014 water quality data collected from surface water runoff at TPAC East. Table 4.5 shows runoff volume for all events that generated runoff from at least one of the TPAC East plots in 2014. The runoff volume weakly correlates with precipitation values (Figure 4.5), while *Miscanthus* had an R value of 0.71 and sorghum an R value of 0.72. Each typically showed lower volumes of runoff during times of lower precipitation. Runoff volume also appears to be weakly correlated with the maximum intensity of precipitation during a storm event, but all r values were less than 0.5 (Figure 4.6). Some of the weather metrics were included here. For those not included, data can be found in Appendix A. Some data have been excluded as outliers, but are also included in Appendix A. September 11, 2014 data have been removed as outliers. There is no precipitation or soil moisture data to indicate the high runoff volumes observed by Leveloggers.

Table 4.5 Runoff volumes measured per plot at TPAC East. Data shown are for all 2014 samples. Volumes are calculated per each 24 storm event.

Date	Precipitation (mm/24 hr period)	poplar (L)	switchgrass (L)	maize (L)	sorghum (L)	*Miscanthus* (L)
4/29/2014	9.7	8.7	2.1	4.8	5.6	6.7
5/12/2014	33.8	20.6	7.2	27.8	10.1	15.8
5/14/2014	13.2	0.0	0.0	0.0	6.9	5.1
5/16/2014	20.1	0.0	0.0	0.0	9.5	7.9
5/19/2014	0.76	2.6	0.0	17.9	0.0	0.0
6/4/2014	14.5	8.1	0.0	8.9	9.1	11.5
6/9/2014	25.1	17.0	4.2	8.7	12.2	11.1
6/11/2014	16	4.3	8.3	5.7	7.7	5.7
6/25/2014	6.6	13.5	0.0	7.6	5.3	8.3
7/7/2014	10.9	8.7	0.0	7.9	9.7	8.3
7/28/2014	20.3	11.6	0.0	5.7	7.1	10.6
7/31/2014	10.7	5.4	0.0	2.9	2.0	2.8
8/12/2014	15.5	5.0	0.0	4.1	4.7	8.0
8/20/2014	8.9	9.7	0.0	5.1	5.5	8.3
8/25/2014	6.6	8.4	0.0	3.7	3.9	4.8
8/27/2014	11.7	5.1	0.0	0.0	5.1	5.4
9/11/2014	20.3	18.5	5.1	26.3	67.0	17.8
9/17/2014	11.7	7.6	0.0	3.4	2.5	0.0
9/22/2014	9.9	0.0	0.0	0.0	0.0	0.0

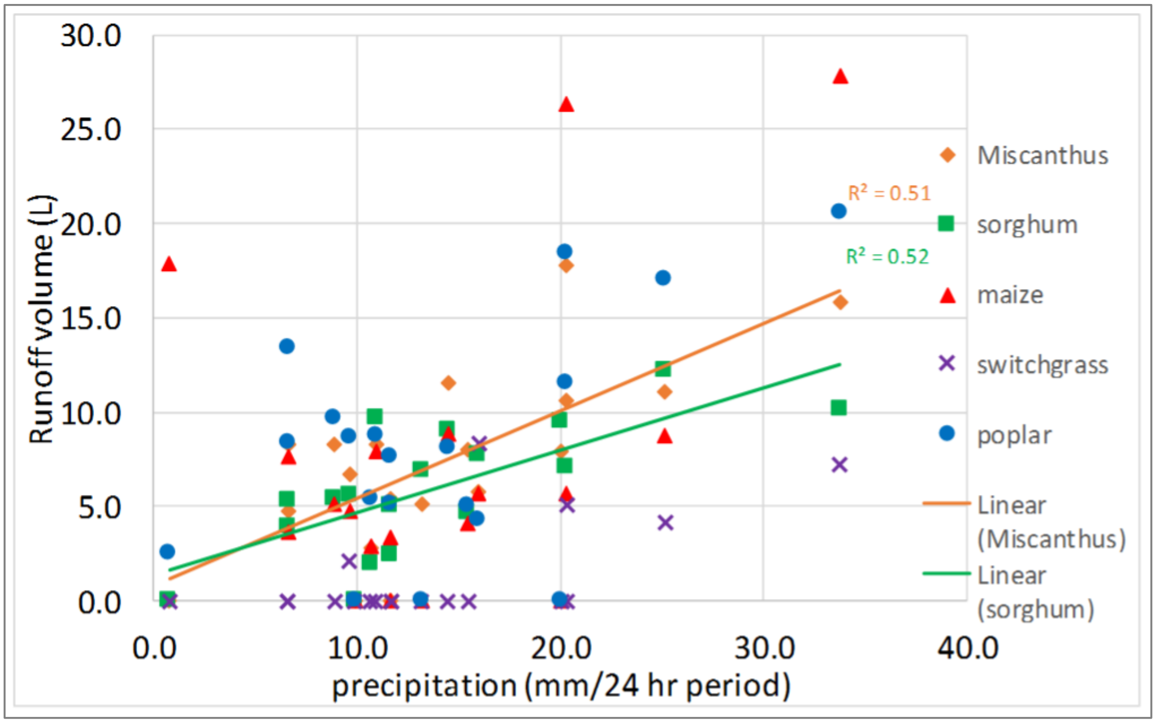


Figure 4.5 Scatterplot of runoff volume from an individual plot at TPAC East as affected by precipitation in a 24 hr period.

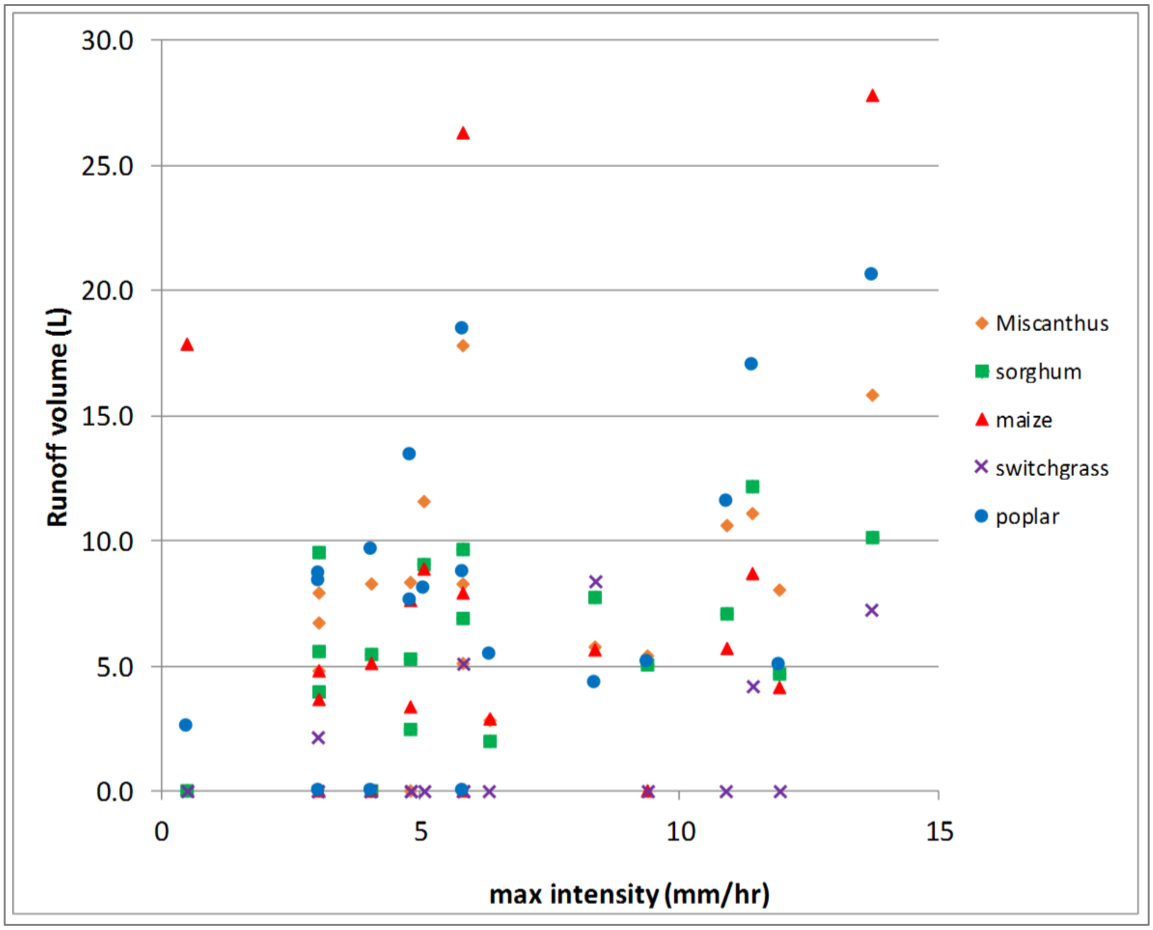


Figure 4.6 Scatterplot of runoff volume from an individual plot at TPAC East as affected by the maximum intensity of precipitation during a storm event.

4.1.2.1 Nitrate-N and Total nitrogen (TN)

Reflecting both fewer runoff events and generally low runoff volumes (Table 4.5), NO_3-N load losses in surface water from the switchgrass plots tended to be lower when compared to all other crops. Nitrate-N mean load losses ranged from 5.9 mg ha^{-1} N in switchgrass to 219 mg ha^{-1} N in sorghum. However, the mean load loss in switchgrass was not significantly different from that of maize, 123 mg ha^{-1} N, and poplar, 119.3 mg ha^{-1} N (Figure 4.7). The mean NO_3-N load for *Miscanthus* (217.2 mg ha^{-1} P) and sorghum were significantly higher (p<0.05) than switchgrass. Event based NO_3-N load losses for *Miscanthus* had among the highest load losses across all events, with the loads consistent throughout the growing season following fertilization. Peak event-based NO_3-N load losses from maize occurred during August, while sorghum's peak load losses occurred in early June (Figure 4.8). Total N loads were not statistically different among the five crops (p<0.05). Switchgrass had low values, with a mean of 416.2 mg ha^{-1} N due to the low runoff generated from these plots. *Miscanthus* TN loads varied greatly over the year sampling period, with a mean of 1149.8 mg N ha^{-1} and a maximum load of 8764 mg N ha^{-1}. Load values for all crops varied throughout the growing season, but did show some slight correlation between the TN load and the total amount of precipitation during the storm event (Figure 4.9). Poplar total N load losses remained relatively low, with a mean of 811.6 mg ha^{-1} N throughout the sampling period. Maximum TN load losses ranged from 2540 mg ha^{-1} N in switchgrass to 9309 mg ha^{-1} N in maize.

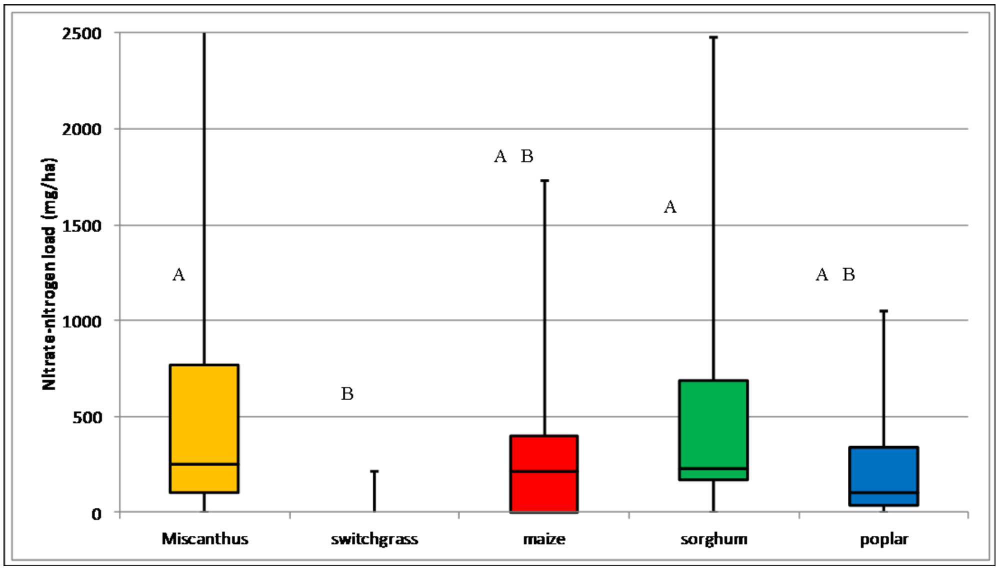


Figure 4.8 Nitrate-N event-based runoff load over the sampling year as affected by crop at TPAC East. Data shown are from 2014 samples collected from 1 replicate. Means with different letters are significantly different (Tukey's HSD, p<0.05).

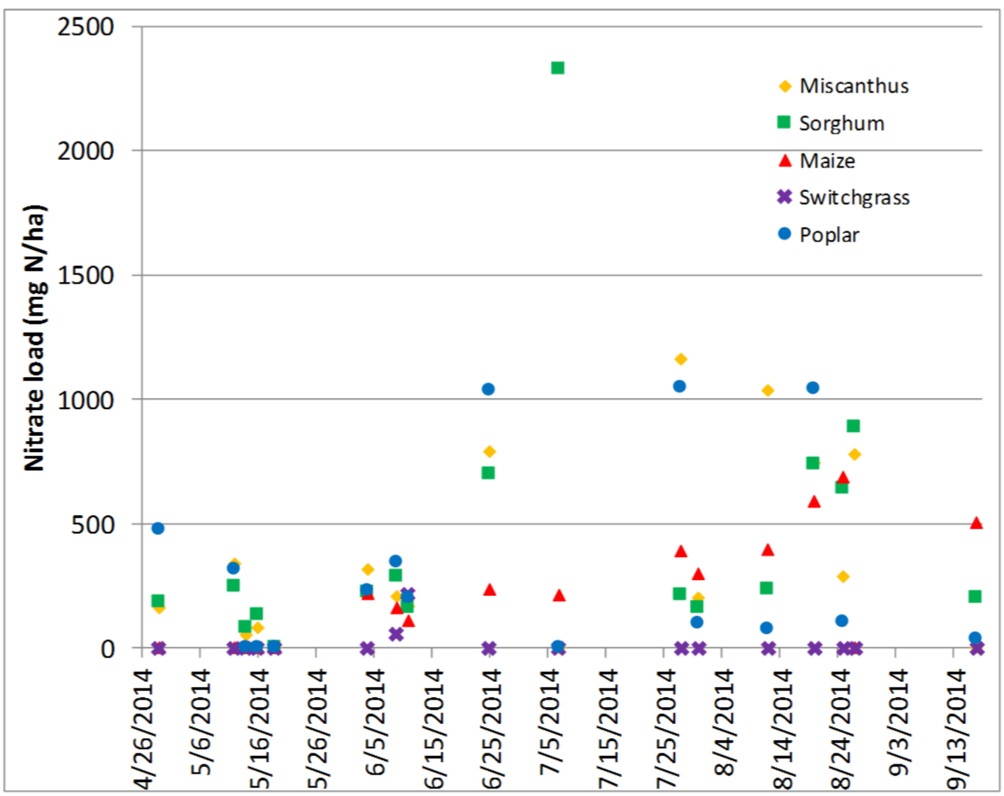


Figure 4.7 Time series showing event-based NO_3-N loss in surface runoff at TPAC East. Data shown are for 2014 samples collected from one replicate of all crops. Each load is calculated per storm event.

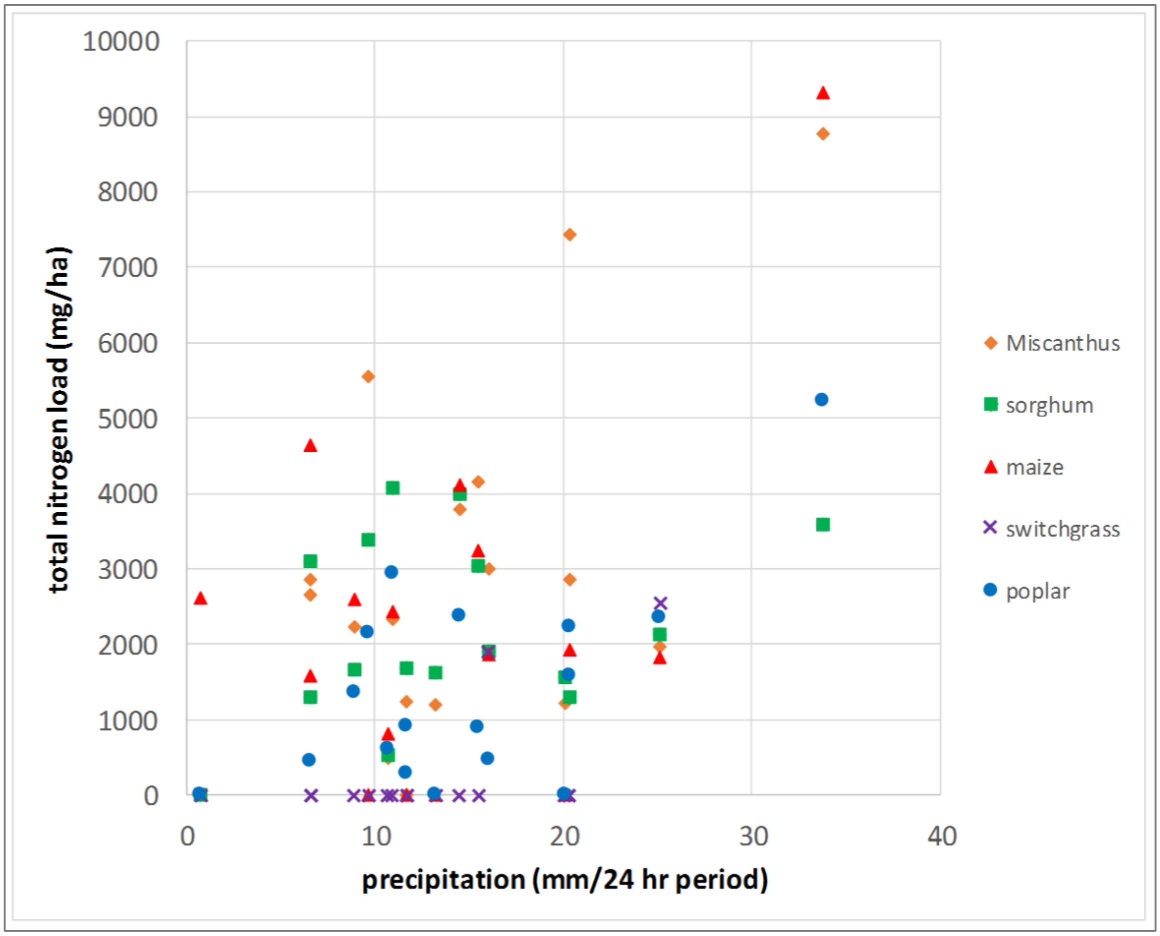


Figure 4.9 Scatter plot showing TN load as affected by the amount of precipitation received during a 24 hr period. Data shown are for 2014 samples collected from one replicate of all crops. Each load is calculated per storm event.

4.1.2.2 Soluble reactive phosphorus (SRP) and total phosphorus (TP)

It is expected that TP losses from runoff will likely be considerably higher than SRP losses when the runoff contains considerable amounts of sediment. These data indicated that soil P levels were very high prior to the start of these treatments, with levels ranging from 50 mg P g^{-1} (ppm) to 58 mg P g^{-1} (ppm) in the replicate equipped for water sampling. There was no clear time of peak SRP loading, but higher loads occurred during the early part of the season (May). Figure 4.10 indicates the SRP loads to surface runoff may be weakly correlated with the amount of precipitation in a storm event. Maximum SRP load losses range from 300 mg ha^{-1} P in poplar to 2591 mg P ha^{-1} in sorghum. The SRP loads are not statistically different among crops (p<0.05), with means for each crop ranging from 75 mg P ha^{-1} P to 593 mg P ha^{-1}. Event-based TP maximum load losses, ranging from 462 mg ha^{-1} P in poplar to 3684 mg ha^{-1} P in sorghum, occurred in the early growing season. All crops tended to follow the same trend of higher values early in the growing season (May-June) and decreasing values through the rest of the growing season (Figure 4.9).

Table 4.6 Soil phosphorus (STP) test results from 2012. Data shown includes means of all four replicates.

crop	mean conc. (Bray P1 equiv. —mg/g P)	range (Bray P1 equiv. —mg/g P)
Miscanthus	36	17-54
switchgrass	43	26-58
maize	39	27-55
sorghum	33	19-53
poplar	40	27-50

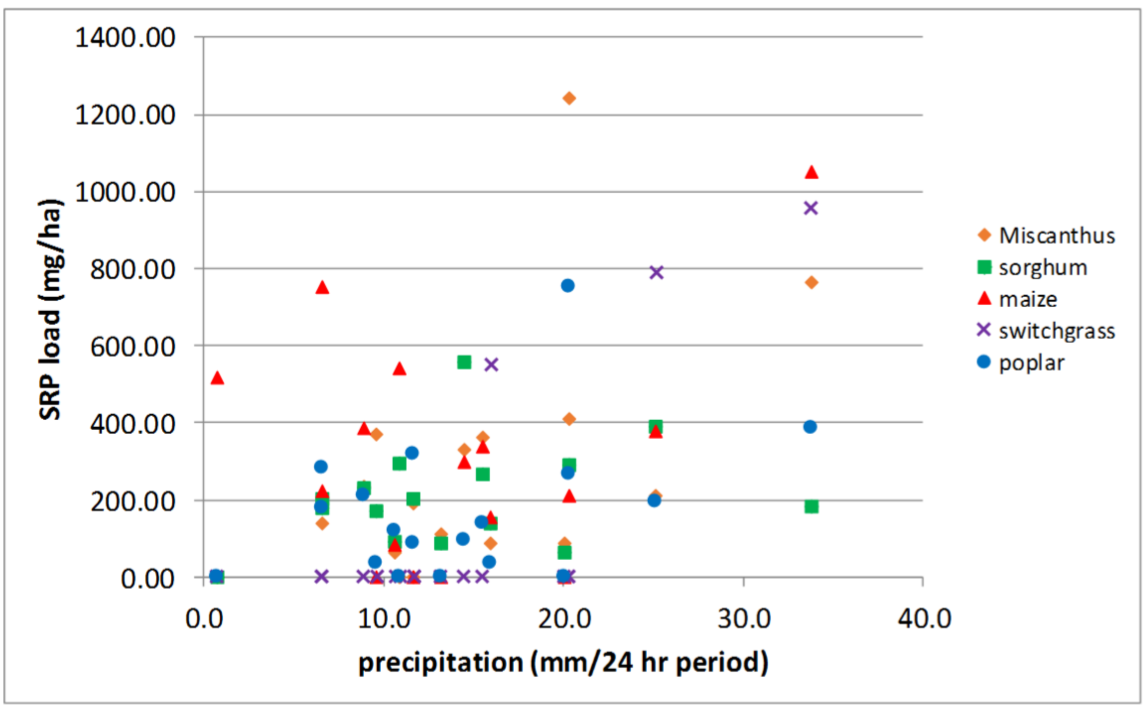


Figure 4.10 Scatter plot showing how precipitation during a storm event affects SRP load to surface waters. Data shown include all 2014 samples collected from one replicate of all crops. Each load is calculated per storm event. The r values for these series are less than 0.6, except switchgrass which is 0.72, but biased by the large number of 0 values for runoff volume.

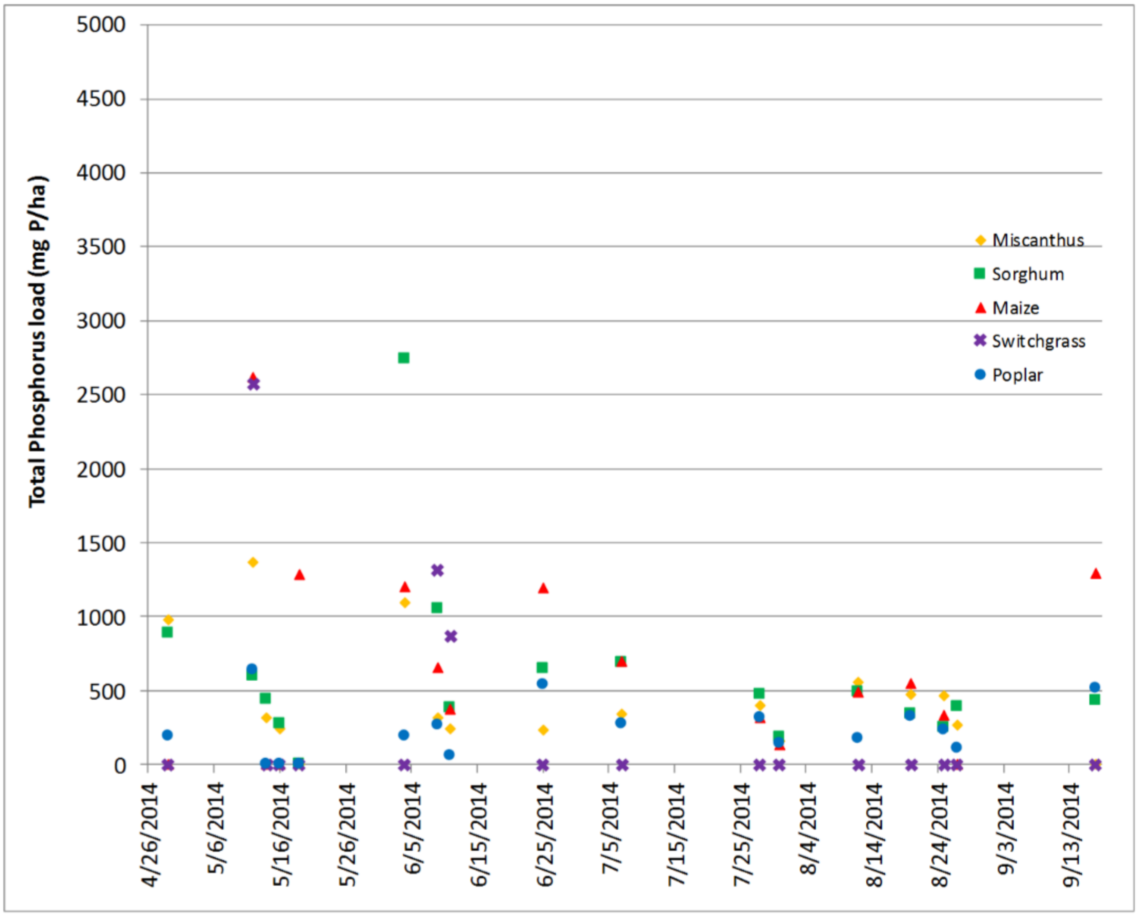


Figure 4.11 Time series of TP load losses in surface runoff at TPAC East. Data shown are for 2014 samples collected from one replicate of all crops. Each load is calculated per storm event.

4.1.2.3 Total suspended solids

Losses of TSS were also not statistically different among crops. As shown in time-series, all crops followed a similar trend, with higher erosion in the early season (May) that generally decreased during the subsequent months (Figure 4.10). Event-based TSS maximum load losses over the entire sample period ranged from 7.4 E^4 mg ha^{-1} in poplar to 1.7 E^6 mg ha^{-1} in maize, while the means over the sample period ranged from 1.9 E^4 mg ha^{-1} to 6.8 E^5 mg ha^{-1}.

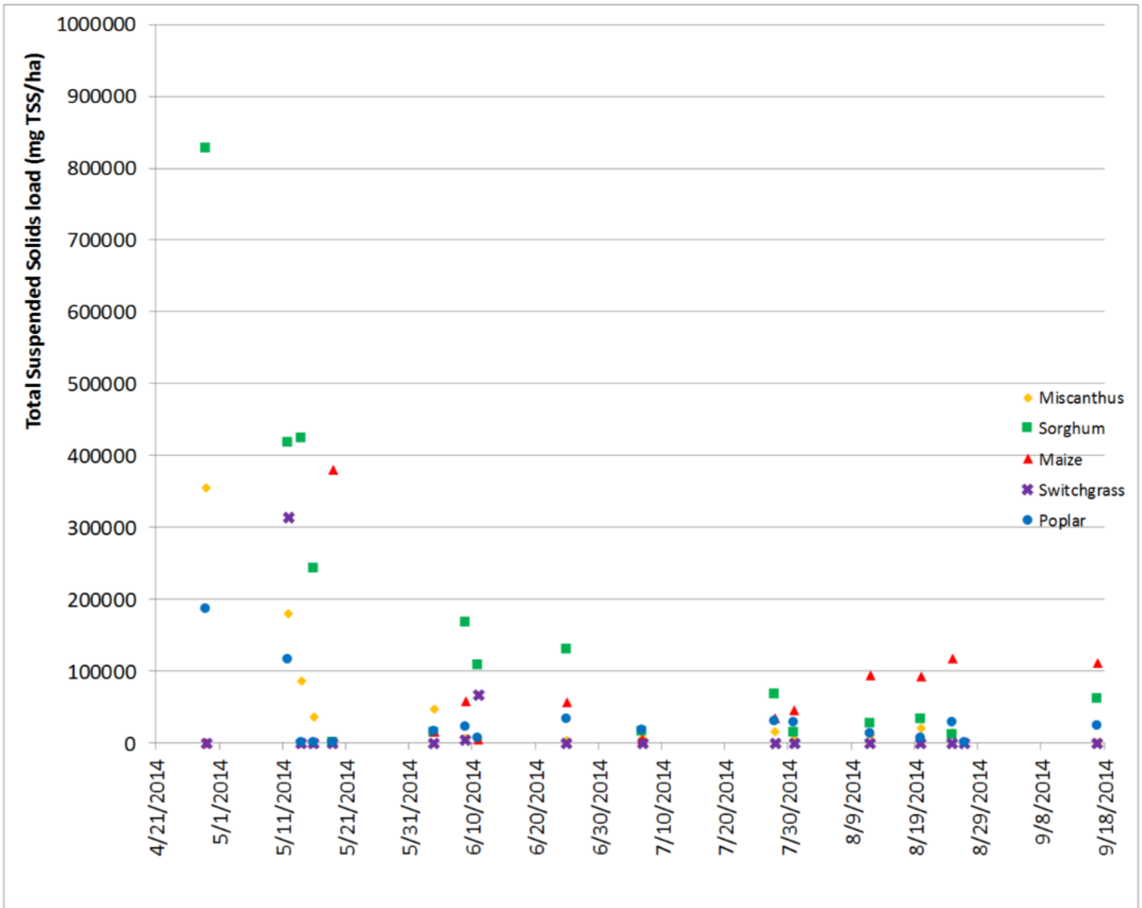


Figure 4.12 Time series showing event-based over a 24 hour period TSS load losses in surface runoff at TPAC East. Data shown are for 2014 samples collected from one replicate of all crops. Each load is calculated per storm event.

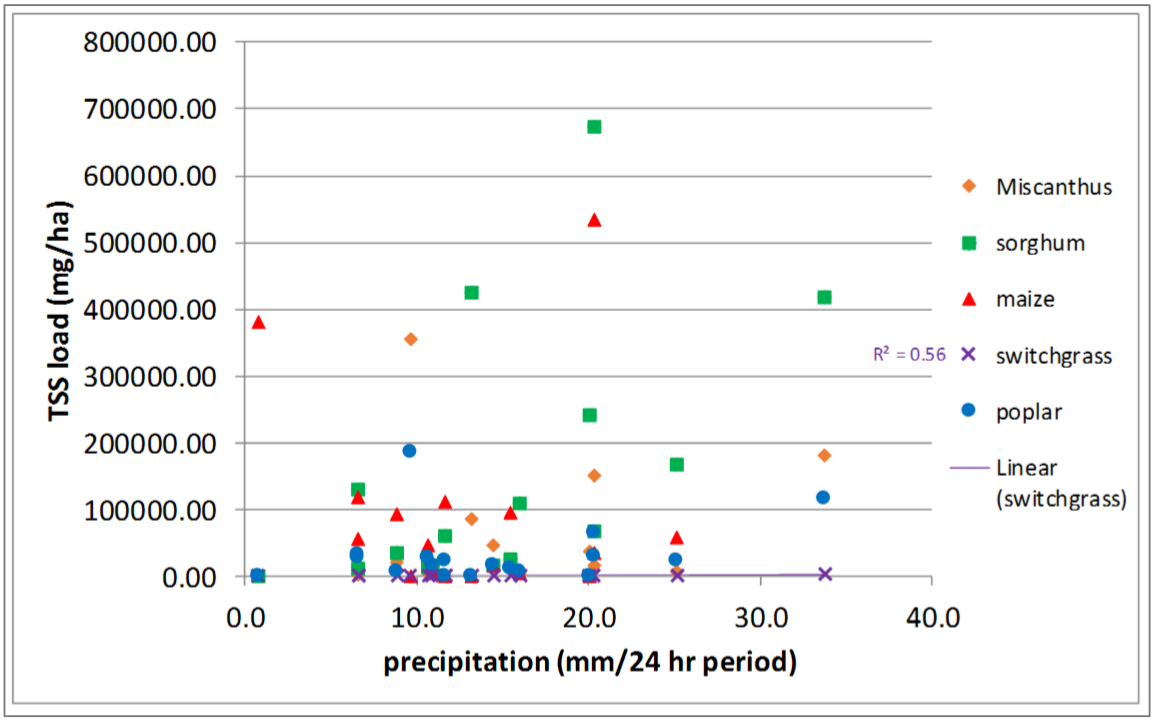


Figure 4.13 Scatterplot of TSS load as affected by precipitation occurring over a 24 hr period. There was no clear correlation, except that switchgrass remains very low due to lack of runoff events, leading the r value to be 0.74. The highest loads originated in the maize and sorghum plots.

4.1.3 Biomass production as a function of species and fertilizer rate

At TPAC West, all crops except *Miscanthus* showed an expected response to N fertilizer, with higher yields in the plots that received N fertilizer when compared to the crop-specific, 0 N control (Figure 4.14). Irrespective of fertilizer, *Miscanthus* produced greater amounts of biomass (an average of 24 Mg ha^{-1} for TPAC West and 18 Mg ha^{-1} for TPAC East) when compared to all other crops at both locations (TPAC West and TPAC East). Switchgrass yielded an average of 10.7 Mg ha^{-1} at TPAC West and 13.5 Mg ha^{-1} at TPAC East. Maize yielded an average of 9.5 Mg ha^{-1} at TPAC West and 4.7 Mg ha^{-1} at TPAC East, while sorghum yielded 12.3 Mg ha^{-1} at TPAC West and 6.6 Mg ha^{-1} at TPAC East.

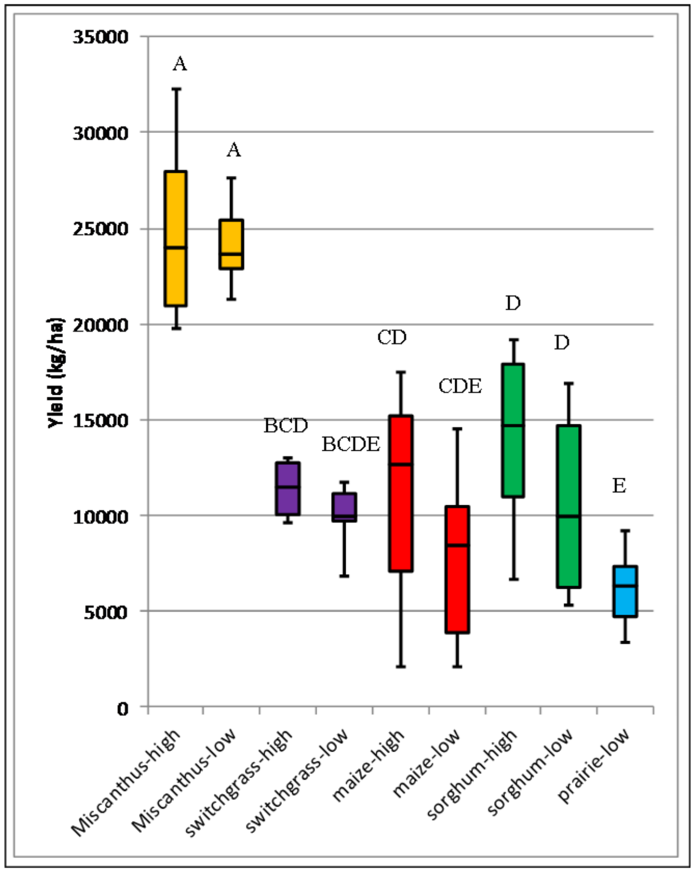


Figure 4.14 TPAC West yield. Data shown are for 2013-2014 samples collected from all crops. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

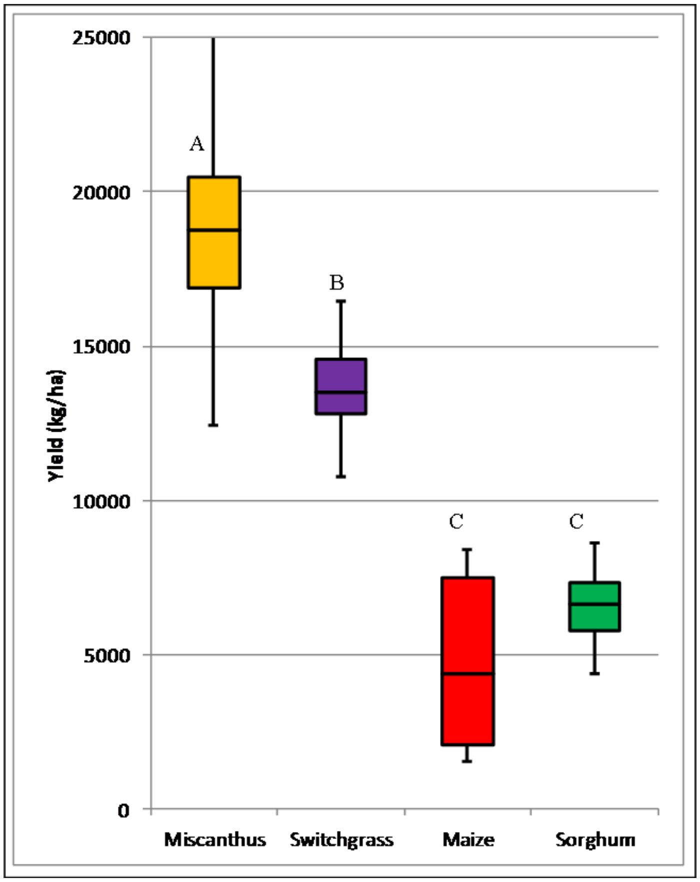


Figure 4.15 TPAC east yields. Data shown for all treatments and replicates sampled in 2013 & 2014. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

Table 4.7 Mean crop yields. Data shown for both TPAC West & East samples collected from all treatments in 2013 & 2014. High and low refers to N fertilizer rates given in Table 3.1.

crop/treatment	treatment	mean yield (Mg/ha)	crop/treatment	mean yield (Mg/ha)
TPAC West			**TPAC East**	
Miscanthus	high	24.8	**Miscanthus**	18.8
Miscanthus	low	24.1		
Shawnee switchgrass	high	11.4	**Liberty switchgrass**	13.5
Shawnee switchgrass	low	10.0		
maize	high	11.1	**maize**	4.8
maize	low	7.9		
sorghum	high	14.0	**sorghum**	6.6
sorghum	low	10.7		
prairie	low	6.1		

4.2 Discussion

4.2.1 Nutrient leachate concentration in subsurface waters

There are several noted advantages to using suction cup lysimeters such as those used in this study. The decision to use suction cup lysimeters in this study draws mainly from these benefits: they cause minimal soil disturbance, are easy to install, and allow for sampling at the same location in the field for extended periods of time (Geibe et al., 2006; Grossman and Udluft, 1991; Zotarelli et al., 2007). Suction cup lysimeters have a potential field disturbance of up to 1 m in all directions, however the radius of recharge is much smaller at 0.1-0.5 m (Grossman and Udluft, 1991). There are some uncertainties involved when using suction cup lysimeters for water quality sampling. It can be difficult to determine exactly where the water comes from and there is concern that large soil pores could create preferential flow (Geibe et al., 2006; Magid et al., 1992; Webster et al., 1993). This possibility of preferential flow from large soil pores can result in suction cup samples reflecting a static soil status than moving flux concentration (Magid et al., 1992). Because of the small potential field and recharge area, there is question as to how many samplers are needed in an area to overcome spatial heterogeneity (Webster et al., 1993).

4.2.1.1 Nitrate-N

This study indicates relatively less NO_3-N leaching to subsurface waters from perennial grasses when compared to maize on marginal lands. Nitrogen often acts along with P to regulate phytoplankton growth in water, especially in seawaters where N is generally found to be the limiting nutrient for primary productivity (Turner and Rabalais, 1991). Nitrogen fertilizer is also more prevalently applied to farmland in the Midwest compared to the rest of the country (Turner and Rabalais, 1991). Because of an intensive root system and lower fertilizer requirements for perennial grasses, it can be expected that nutrient losses will be lower when compared to annual crops with greater fertilizer requirements. In a winter-time study by Christian and Riche (1998), the authors also observed low NO_3-N losses to subsurface water from *Miscanthus* plots (less than 5 mg L^{-1}), similar to data from winter month's samples from all three *Miscanthus* experiments in this study. Christian and Riche (1998) described a maximum concentration of 60 mg L^{-1} in the first year from the highest N-fertilized (120 kg N ha^{-1}) *Miscanthus* plots in their study. This maximum peak decreased in subsequent years to a low of 40 to 50 mg N L^{-1} observed three years after stand establishment (Christian and Riche, 1998). This study is comparable to the work reported here because the soil type is similar and the study was completed using suction cup lysimeters, although a greater difference could occur because they were sampled at a more shallow depth of 16 cm. The fertilization rate is similar to the *Miscanthus*-high plots of this study. The data from TPAC West and TPAC East indicated that on these marginal lands, the maximum concentrations were lower than the 60 mg N L^{-1} value reported by Christian and Riche (1998) over the entire study period (Tables 4.1 & 4.2), with the *Miscanthus*-high plots having a maximum value within the 40-50 mg N L^{-1} values observed by the authors. In a field study completed at Iowa State University using subsurface drainage flow-weighted samples, switchgrass plots yielded low NO_3-N concentrations (<5 mg L^{-1}), with a slight increase in the summer following spring fertilization (Helmers et al., 2009).

In accordance with the findings reported here, a few studies identified a significantly (p<0.05) greater NO_3-N leaching loss from maize and sorghum plots than switchgrass and *Miscanthus* (McIsaac et al., 2010; Thomas et al., 2014; Trybula, 2012). However, unlike this study at TPAC, these plots were located on prime agricultural land (McIsaac et al., 2010; Trybula, 2012). It is expected to see greater nutrient losses from marginal lands than prime agricultural lands due to high fertilizer rates and smaller crop growth. In a study using data from a nearby location, the Water Quality Field Station (WQFS) (21 km), but on land considered prime for traditional row cropping, continuous maize showed subsurface nitrate drainage concentrations ranging from 4.1 mg L^{-1} to 25.5 mg L^{-1} (Trybula, 2012). This is similar to the observed values at TPAC, however the maize-high plots on TPAC west had even higher nitrate losses to subsurface drainage than the values reported by Trybula (2012). These higher observed NO_3-N leaching losses could be attributed to poor crop growth on marginal land. As observed, yields are lower on marginal land, as low as 25% of the expected yield, so there is less plant N removed with harvest. Another study completed on prime agricultural land with sorghum and maize indicated an average of 6.0 mg L^{-1} of nitrate loss to subsurface waters, similar to the unfertilized plots in this study (Long, 2015).

A study by Jaynes et al. (2001), demonstrated a correlation between fertilizer rate and nitrate concentration in subsurface drainage water with maize crops. This TPAC study reaffirms those results with observed statistical difference between both maize (0 N) and sorghum (0 N) and their higher fertilized counterparts (Figure 4.1). This can also be seen in the higher concentrations observed in the fertilized maize and sorghum plots in TPAC east.

Contrary to this study's findings, in both a computer modeling study and field study, switchgrass has sometimes been shown to have a slight increase in subsurface nitrate loading when fertilized at the same rate as *Miscanthus* (Cibin et al., 2015; Trybula, 2012). The greater loss from switchgrass was attributed to the possibility that *Miscanthus* has a higher nitrogen uptake than switchgrass. This was not observed in the concentration measurements taken in this study. However our measurements were only of concentration without volume for load calculations to be directly compared to the study by Cibin et al. (2015).

4.2.1.2 Soluble reactive phosphorus

While phosphorus is a major water quality parameter of concern in the Midwest, measurements on subsurface losses are very limited. In general, this study did not indicate significant SRP leaching to subsurface waters from crops not receiving fertilizer. This is likely due to low soil P levels (Appendix C). The *Miscanthus* treatments with varied levels of P fertilizer applied (0, 30 kg ha^{-1}) indicated some phosphorus loss from plots that are fertilized. However, it has been noted that phosphorus does not travel quickly vertically through the soil profile (Eghball et al., 1996; Heckrath et al., 1995). Because these lysimeters are located at a 30 cm depth, it is possible some of the soil P effects can only be seen in the upper soil surface layers and not at this depth. Appendix C shows soil P levels as a result of treatment in the perennial plots. In a 2-year study completed in a nearby location, on prime agricultural land, maize and soybean, treated with different fertilizers and rates and untreated prairie grasses were compared for subsurface nutrient loss (Hernandez-Ramirez et al., 2011). In a 2-year study, the authors indicate no significant difference between the treatments and phosphorus loss except for continuous maize fertilized in the fall with swine manure (Hernandez-Ramirez et al., 2011). The TPAC east plots received no phosphorus fertilizer; therefore the concentrations and statistical differences seen in Figure 4.4 are more likely related to the Soil test P (STP) levels shown in Table 4.6 and Appendix C. Simulation studies have indicated a reduction in SRP ranging from 2.6% to 36% when bioenergy crops replace maize/soybean rotations (Cibin et al., 2015). However, empirical studies including no phosphorus fertilizer application, indicate very low phosphorus levels in subsurface drainage from all crops (Trybula, 2012). A recent review by King et al. (2015) indicated increased interest in phosphorus transport via subsurface pathways, especially tile drainage. The authors indicated that while interest and studies have increased, the complex nature of subsurface phosphorus transport made definitive results difficult to obtain. Losses of phosphorus were reported to be greater in the non-growing season and dependent on weather variables, such as rain storm events (King et al., 2015).

4.2.2 Nutrient losses to surface runoff

4.2.2.1 Nitrate-N and total nitrogen

Perennial grasses are expected to have lower NO_3-N loads to surface runoff when compared to annual row crops. Previous work has demonstrated switchgrass can reduce the amount of sediment and nutrients in runoff, corresponding with findings in this study. A field study by Lee et al. (1999) showed a 31-51% reduction in TN, and a 28-47% reduction in NO_3-N when using switchgrass as a buffer strip for traditional row cropping when compared to traditional row cropping without a buffer. Watershed modeling studies have suggested that both switchgrass and *Miscanthus* can decrease the amount of sediment and NO_3-N in runoff as well as the overall amount of runoff (Cibin et al., 2015; Nelson et al., 2006; Thomas et al., 2014; Trybula, 2012). These modeling predictions are contrary to what was observed at TPAC East where the *Miscanthus* treatment NO_3-N surface losses were not significantly different from annual row cropping treatments. However, *Miscanthus* on this plot did not produce biomass yield at the rate expected for the Midwest region or at TPAC West; some of these nutrient losses can be attributed to a poor biomass production. While switchgrass had lower surface runoff losses, it was only significantly different from sorghum and *Miscanthus*. These results are potentially different from modeling results due to performance of the crops on marginal land. *Miscanthus* on marginal land at TPAC East produced only 75% the amount of above-ground biomass as TPAC West, and only 63% the biomass expected on prime agricultural land (Heaton et al., 2008). The trend in surface nutrient loss was weakly correlated to sediment loading for adsorbed nutrients (organic N and P).

4.2.2.2 Soluble reactive phosphorus and total phosphorus

There is some indication of higher P losses to surface runoff early in the growing season, April through early June. Because the perennial grasses are much smaller during this time and because the maize and sorghum had recently been planted (thus, disturbing the soil), more soil was exposed directly to rainfall, increasing the likelihood of soil erosion and phosphorus load increases. It has already been shown that soil test P levels directly correlate to the amount of dissolved P in runoff (Edwards et al., 1993; Pote et al., 1999; Shreiber, 1988; & Yli-Halla et al., 1995). The soil in TPAC East plots had a high phosphorus concentration (50-58 Bray-1 equiv ppm-P) (Table 4.6), and, according to regional fertilizer recommendations, would require no additional fertilizer (Vitosh et al., 2000). Because the soil in these plots had high phosphorus, it is expected that rainfall during a time of exposed soil on this higher sloping land would result in greater phosphorus (SRP and TP) loads to surface water. Therefore, one possible reason switchgrass, *Miscanthus*, and poplar showed slightly lower phosphorus loads could be due to the lack of soil disruption and extensive root systems that help prevent soil erosion (Romkens et al., 1973; Andraski et al., 1985; Puustinen et al., 2005). Switchgrass has been simulated to reduce TP by 39-55% and SRP by 38-36% when used as a buffer strip, when compared to agricultural land without a buffer (Lee et al., 1999; Thomas et al., 2014). However, on the TPAC East plots, SRP and TP did not show statistically different results among crops.

4.2.2.3 Total suspended solids

The data shows no clear pattern over the year of this study for TSS, and no one crop had a statistically significant effect on TSS ($p<0.05$). The data show greater loads during the early months of the growing season, when there is more exposed soil. The loads generally decreased throughout the growing season. Maize and sorghum show greater loads again later in the season likely due to the exposed soil between rows and greater runoff volumes shown in Table 4.5. Other field studies have also indicated that land cover and less tillage help prevent erosion (Nyakatawa et al., 2006; Puustinen et al., 2005). Poplar forms a protective soil barrier, with its canopy, fallen leaves on soil surface, and an extensive root system (Wilkinson, 1999; Kort et al., 1998). At the time of this study, the poplars were in years 3 and 4 of growth and therefore the surface soil was not disturbed by a recent planting or harvesting.

Modeling studies have estimated the amount of soil erosion to increase as more maize stover is removed for biofuels (Cibin et al., 2012; Wu and Liu, 2012). This soil erosion estimation may likely also apply to sorghum, as it is managed for planting and tillage in the same way as maize and has similar growth patterns. Erosion rates have been estimated by watershed models to be similar for *Miscanthus* and switchgrass, with a reduction ranging from 0.2% to 24% when these bioenergy crops were grown in place of traditional row crops (Cibin et al., 2015), and even greater decreases seen with that scenario, 30-70%, in a study by Thomas et al. (2014). Perennial grasses, requiring no tillage and keeping a root system underground all year, show a great reduction in soil erosion (Cibin et al., 2015; Lee et al., 1999; Nyakatawa et al., 2006; Wu and Liu, 2012). The results of this study are consistent with both published data and simulation results, with perennial grasses exhibiting less erosion than annual row crops. The data is not statistically significant in this TPAC East study, possibly due to the low number of samples over only one year of data collection and only one replicate. This data be considered highly preliminary.

4.2.3 Production as a factor of species and fertilizer rate

This study indicates a greater production of biomass from *Miscanthus* than any other crop at both experimental sites. The *Miscanthus* yield results from this study were comparable to a study by Heaton et al. (2008), which indicated *Miscanthus* grown in the Midwest can produce an average of 29.6 t ha^{-1}. The TPAC West yields were comparable in value at an average of 24.4 t ha^{-1}. However, the TPAC East plots underperformed, producing an average of 18.8 t ha^{-1}. This is likely due to the higher slope and drier soils at TPAC East. A SWAT modeling study using an improved model representation of perennial grasses indicated that, on higher sloping land (>2%), *Miscanthus* can produce around 21.6 t ha^{-1} and switchgrass 10.7 t ha^{-1} (Cibin et al., 2015). Similarly, Heaton et al. (2008) indicated Cave-in-Rock switchgrass, an upland ecotype, could produce around 10.4 t ha^{-1} in the Midwest. The TPAC study indicated switchgrass production of that amount or higher. Switchgrass is estimated to produce 5-9.4 t ac^{-1} by the Department of Energy's Billion Ton Update Report (2011). It performed especially well on the TPAC East plots, where Liberty switchgrass was grown. Liberty switchgrass has been shown to have a production potential 20% greater than Shawnee switchgrass variety (Vogel et al., 2014). The yields of Liberty switchgrass at TPAC East are slightly lower than the 18.1 t ha^{-1} indicated by Vogel et al. (2014), however this can be attributed to poorer growth on marginal lands. Lower yields of most cellulosic biofuel crops can occur because soils on a slope are typically drier (Plaster, 2014). However, switchgrass is reported to have a lower water requirement per unit biomass (Heaton, et al., 2004) and is therefore better able to perform on marginal lands. The Shawnee switchgrass yields on TPAC west are similar, with fertilizer, to expected yields of 12.5 t ha^{-1} (Vogel et al., 2014). In a study by Heaton et al. (2004), *Miscanthus* had a greater yield response to water quantity and switchgrass had a greater yield response to N fertilizer rates. In another field study located at WQFS, the same variety of sorghum was observed to produce between 14-22 Mg ha^{-1} of aboveground biomass, with an average yield over five years of 17.67 Mg ha^{-1} (Long, 2015). The sorghum yields of this TPAC study were much lower, particularly on TPAC east. Maize had indicated an aboveground biomass yield of 10-20 Mg ha^{-1}, with a five year average of 16.68 Mg ha^{-1} (Linden et al., 2000; Long, 2015). At both TPAC West and TPAC East sites, the maize yields were low compared with expected yields on agricultural land in the region, with TPAC East having markedly lower yields. It is generally expected that annual row crop yield will be less on marginal land than on prime agricultural land. The maize yields in this TPAC study were much lower, between 8-11 t ha^{-1} at TPAC West and 4 t ha^{-1} at TPAC East. Sorghum can be found to produce greater biomass during high stress times. During the drought in 2012 when there was only 812 total mm of total precipitation, sorghum out produced maize by 5-7 t ha^{-1} (Long, 2015). In 2014, the yields for row crops (maize and sorghum) were much lower than in 2013, this may reflect weed pressure in the plots (Ryan Dierking, Purdue University, personal communication, 4 February 2015).While in this TPAC study, sorghum typically yielded higher than maize, both were significantly outperformed by *Miscanthus* (p<0.05).

CHAPTER 5. SUMMARY, CONCLUSIONS, POTENTIAL LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Summary & Conclusions

This study has demonstrated that with or without fertilizers, perennial grasses (switchgrass and *Miscanthus*) have a less negative water quality impact (nutrient loss and soil erosion) than maize and sorghum with added fertilizer. The perennial grasses also demonstrate a greater biomass production potential than annual row crops when grown on lands considered agriculturally marginal. This leads to the conclusion that perennial grasses treated with N fertilizer, particularly *Miscanthus*, may be better alternatives for biofuel production on marginal land.

- Objective 1: Perennial grasses show less subsurface NO_3-N losses than annual row crops, with averages of 2.4 mg N L^{-1} and 19.1 mg N L^{-1}, respectively. Most of the study plots did not receive P fertilizer, therefore subsurface SRP concentrations are more likely related to STP levels. However, of the perennial plots treated with P fertilizer, *Miscanthus* shows significantly more SRP losses than switchgrass. *Miscanthus* had a mean loss of 0.33 mg P L^{-1} and switchgrass had a mean loss of 0.1 mg P L^{-1}.

- Objective 2: In one year of data collection, the five crops evaluated in this study generally showed no significant effect on nutrient losses or soil erosion. Switchgrass had significantly less NO_3-N surface loads than *Miscanthus* and sorghum, with mean loads of 14.8 mg N ha^{-1}, 543.1 mg N ha^{-1}, and 549.8 mg N ha^{-1}, respectively. No other nutrient or test parameter was significantly affected by crop treatment in one year of this study.
- Objective 3: *Miscanthus* has the highest production potential, with a mean yield of 22.5 t ha^{-1}. Switchgrass produced a mean biomass of 11.6 t ha^{-1}, while maize and sorghum produced 7.9 t ha^{-1} and 10.4 t ha^{-1}, respectively. Native prairie grasses produced the least biomass at 6.1 t ha^{-1}.

5.2 Potential limitations of study

There are a few potential limitations of this study. The timeframe of this study was limited to only two years of subsurface nutrient concentration data and only one year of surface loading data. The subsurface data collected was only concentration and did not include loads. The phosphorus loss as a result of nutrient application is limited to only TPAC West switchgrass and *Miscanthus* and does not include any maize or sorghum plots; therefore this data is not indicative of all crop effects on phosphorus losses. TPAC East only has one replicate equipped for water quality monitoring, allowing only for statistics with pseudo-replicates and basic mean comparisons instead of replicates for significance. There are no poplar yield data included due to time restrictions for this study. Because the poplar plot had not been harvested, the harvest effects on water quality were not examined.

5.3 Future research

Future research in the field study of biofuel crops on marginal land and the environmental consequences of this production can include improvements to this study, such as an expansion of this field setup to include all four replicates of surface water monitoring. Another potential improvement to this study is to determine P application effects on all crops. This expansion will allow for statistical significance testing between replicates. Coupling these data with an environmental model, such as the SWAT model, would improve model representation of biofuel management and production on marginal lands. To take this study another step further, more types of marginal lands could be evaluated, such as those mentioned by Milbrandt et al. (2014).

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APPENDICES

Appendix A Weather Matrices and Surface Runoff

weather data					runoff volumes (L)				
storm event date	24 hr total precip	max intensity (mm/hr)	duration (hrs rain/24 hrs)	avg intensity (total precip/ hrs rain)	miscanthus	sorghum	maize	switchgrass	poplar
4/29/2014	9.7	3.0	10	1.0	6.7	5.6	4.8	2.1	8.7
5/12/2014	33.8	13.7	7	4.8	15.8	10.1	27.8	7.2	20.6
5/14/2014	13.2	5.8	13	1.0	5.1	6.9	0.0	0.0	0.0
5/16/2014	20.1	3.0	20	1.0	7.9	9.5	0.0	0.0	0.0
5/19/2014	0.8	0.5	2	0.4	0.0	0.0	17.9	0.0	2.6
6/4/2014	14.5	5.1	5	2.9	11.5	9.1	8.9	0.0	8.1
6/9/2014	25.1	11.4	7	3.6	11.1	12.2	8.7	4.2	17.0
6/11/2014	16.0	8.4	12	1.3	5.7	7.7	5.7	8.3	4.3
6/25/2014	6.6	4.8	6	1.1	8.3	5.3	7.6	0.0	13.5
7/7/2014	10.9	5.8	3	3.6	8.3	9.7	7.9	0.0	8.7
7/28/2014	20.3	10.9	5	4.1	10.6	7.1	5.7	0.0	11.6
7/31/2014	10.7	6.4	3	3.6	2.8	2.0	2.9	0.0	5.4
8/12/2014	15.5	11.9	8	1.9	8.0	4.7	4.1	0.0	5.0
8/20/2014	8.9	4.1	4	2.2	8.3	5.5	5.1	0.0	9.7
8/25/2014	6.6	3.0	5	1.3	4.8	3.9	3.7	0.0	8.4
8/27/2014	11.7	9.4	4	2.9	5.4	5.1	0.0	0.0	5.1
9/11/2014	20.3	5.8	14	1.5	17.8	67.0	26.3	5.1	18.5
9/17/2014	11.7	4.8	8	1.5	0.0	2.5	3.4	0.0	7.6
9/22/2014	9.9	4.1	7	1.4	0.00	0.00	0.00	0.00	0.00

weather data					nitrate load (mg ha^{-1})				
storm event date	24 hr total precip	max intensity (mm/hr)	duration (hrs rain/24 hrs)	avg intensity (total precip/ hrs rain)	miscanthus	sorghum	maize	switchgrass	poplar
4/29/2014	9.7	3.0	10	1.0	162.58	181.73	0.00	0.00	476.89
5/12/2014	33.8	13.7	7	4.8	340.56	249.43	2.09	0.00	316.55
5/14/2014	13.2	5.8	13	1.0	54.86	80.88	0.00	0.00	0.00
5/16/2014	20.1	3.0	20	1.0	78.84	133.78	0.00	0.00	0.00
5/19/2014	0.8	0.5	2	0.4	0.00	0.00	0.00	0.00	0.00
6/4/2014	14.5	5.1	5	2.9	315.31	222.78	216.77	0.00	229.49
6/9/2014	25.1	11.4	7	3.6	209.69	286.45	162.19	53.36	341.93
6/11/2014	16.0	8.4	12	1.3	169.25	161.99	108.39	213.92	200.22
6/25/2014	6.6	4.8	6	1.1	787.48	700.33	236.31	0.00	1034.46
7/7/2014	10.9	5.8	3	3.6	0.00	2327.31	215.71	0.00	0.00
7/28/2014	20.3	10.9	5	4.1	1160.09	212.73	392.21	0.00	1046.89
7/31/2014	10.7	6.4	3	3.6	200.43	162.88	300.17	0.00	96.50
8/12/2014	15.5	11.9	8	1.9	1034.79	234.00	398.09	0.00	76.15
8/20/2014	8.9	4.1	4	2.2	744.95	737.19	590.51	0.00	1043.11
8/25/2014	6.6	3.0	5	1.3	286.14	642.70	688.50	0.00	104.29
8/27/2014	11.7	9.4	4	2.9	779.45	884.70	0.00	0.00	
9/11/2014	20.3	5.8	14	1.5	3451.09	2479.36	1732.40	0.00	68.35
9/17/2014	11.7	4.8	8	1.5	0.00	198.80	505.23	0.00	36.20
9/22/2014	9.9	4.1	7	1.4	543.08	549.83		14.85	

weather data					total nitrogen load (mg ha^{-1})				
storm event date	24 hr total precip	max intensity (mm/hr)	duration (hrs rain/24 hrs)	avg intensity (total precip/ hrs rain)	miscanthus	sorghum	maize	switchgrass	poplar
4/29/2014	9.7	3.0	10	1.0	5552.41	3381.01	0.00	0.00	2146.04
5/12/2014	33.8	13.7	7	4.8	8764.88	3579.79	9309.58		5236.68
5/14/2014	13.2	5.8	13	1.0	1193.42	1617.83	0.00	0.00	0.00
5/16/2014	20.1	3.0	20	1.0	1224.11	1563.62	0.00	0.00	0.00
5/19/2014	0.8	0.5	2	0.4	0.00	0.00	2617.43	0.00	0.00
6/4/2014	14.5	5.1	5	2.9	3788.74	3996.85	4111.46	0.00	2371.55
6/9/2014	25.1	11.4	7	3.6	1975.85	2125.71	1832.59	2540.98	2353.14
6/11/2014	16.0	8.4	12	1.3	3006.57	1909.87	1862.21	1886.98	471.91
6/25/2014	6.6	4.8	6	1.1	2853.09	3091.25	4649.19	0.00	
7/7/2014	10.9	5.8	3	3.6	2329.75	4079.49	2441.15	0.00	2933.94
7/28/2014	20.3	10.9	5	4.1	2858.03	1304.70	1920.57	0.00	2236.17
7/31/2014	10.7	6.4	3	3.6	484.69	529.24	813.52	0.00	614.16
8/12/2014	15.5	11.9	8	1.9	4153.31	3033.40	3236.68	0.00	900.48
8/20/2014	8.9	4.1	4	2.2	2223.12	1670.62	2593.01	0.00	1355.48
8/25/2014	6.6	3.0	5	1.3	2658.31	1306.14	1571.15	0.00	443.97
8/27/2014	11.7	9.4	4	2.9	1238.34	1685.09	0.00	0.00	287.95
9/11/2014	20.3	5.8	14	1.5	7437.62			0.00	1590.09
9/17/2014	11.7	4.8	8	1.5	0.00	2470.74	2548.61	0.00	906.79

weather data					srp load (mg ha^{-1})				
storm event date	24 hr total precip	max intensity (mm/hr)	duration (hrs rain/24 hrs)	avg intensity (total precip/ hrs rain)	miscanthus	sorghum	maize	switchgrass	poplar
4/29/2014	9.7	3.0	10	1.0	370.30	170.39	0.00	0.00	37.46
5/12/2014	33.8	13.7	7	4.8	764.01	183.04	1049.66	956.27	386.29
5/14/2014	13.2	5.8	13	1.0	110.99	85.80	0.00	0.00	0.00
5/16/2014	20.1	3.0	20	1.0	86.98	65.34	0.00	0.00	0.00
5/19/2014	0.8	0.5	2	0.4	0.00	0.00	517.48	0.00	0.00
6/4/2014	14.5	5.1	5	2.9	331.81	557.51	298.16	0.00	94.93
6/9/2014	25.1	11.4	7	3.6	212.34	391.14	379.65	791.62	193.88
6/11/2014	16.0	8.4	12	1.3	88.73	141.05	155.17	549.93	35.63
6/25/2014	6.6	4.8	6	1.1	138.77	204.01	753.37	0.00	281.18
7/7/2014	10.9	5.8	3	3.6	0.00	295.64	541.05	0.00	0.00
7/28/2014	20.3	10.9	5	4.1	408.52	291.80	211.17	0.00	266.36
7/31/2014	10.7	6.4	3	3.6	64.15	93.31	82.70	0.00	119.16
8/12/2014	15.5	11.9	8	1.9	363.83	266.71	336.33	0.00	140.98
8/20/2014	8.9	4.1	4	2.2	234.82	230.61	385.59	0.00	211.48
8/25/2014	6.6	3.0	5	1.3	208.13	180.36	223.80	0.00	180.10
8/27/2014	11.7	9.4	4	2.9	192.33	202.02	0.00	0.00	87.79
9/11/2014	20.3	5.8	14	1.5	1243.98	6479.12	2967.35	0.00	752.13
9/17/2014	11.7	4.8	8	1.5	0.00	201.33	393.73	0.00	317.84

weather data					total phos load (mg ha^{-1})				
storm event date	24 hr total precip	max intensity (mm/hr)	duration (hrs rain/24 hrs)	avg intensity (total precip/ hrs rain)	miscanthus	sorghum	maize	switchgrass	poplar
4/29/2014	9.7	3.0	10	1.0	977.39	888.90	0.00	0.00	192.97
5/12/2014	33.8	13.7	7	4.8	1365.10	601.70	2615.11	2572.15	641.76
5/14/2014	13.2	5.8	13	1.0	317.88	444.54	0.00	0.00	0.00
5/16/2014	20.1	3.0	20	1.0	238.02	276.14	0.00	0.00	0.00
5/19/2014	0.8	0.5	2	0.4	0.00	0.00	1286.10	0.00	0.00
6/4/2014	14.5	5.1	5	2.9	1097.57	2745.34	1201.09	0.00	195.92
6/9/2014	25.1	11.4	7	3.6	316.86	1053.58	656.86	1314.46	267.87
6/11/2014	16.0	8.4	12	1.3	239.49	383.34	373.65	862.86	60.89
6/25/2014	6.6	4.8	6	1.1	230.03	649.69	1197.60	0.00	543.53
7/7/2014	10.9	5.8	3	3.6	343.10	688.54	693.20	0.00	276.23
7/28/2014	20.3	10.9	5	4.1	401.64	474.57	312.77	0.00	317.89
7/31/2014	10.7	6.4	3	3.6	158.87	183.82	130.53	0.00	145.00
8/12/2014	15.5	11.9	8	1.9	556.59	490.37	490.31	0.00	173.78
8/20/2014	8.9	4.1	4	2.2	469.64	343.19	545.12	0.00	320.84
8/25/2014	6.6	3.0	5	1.3	462.43	254.16	331.32	0.00	231.20
8/27/2014	11.7	9.4	4	2.9	263.34	388.39	0.00	0.00	113.20
9/11/2014	20.3	5.8	14	1.5	1849.50	9210.88	4581.23	0.00	1156.84
9/17/2014	11.7	4.8	8	1.5	0.00	429.01	1295.29	0.00	512.58

weather data					tss load (mg ha^{-1})				
storm event date	24 hr total precip	max intensity (mm/hr)	duration (hrs rain/24 hrs)	avg intensity (total precip/ hrs rain)	miscanthus	sorghum	maize	switchgrass	poplar
4/29/2014	9.7	3.0	10	1.0	355673.71	826787.34	0.00	0.00	186433.91
5/12/2014	33.8	13.7	7	4.8	180326.10	417142.30	1696139.63	313589.44	116402.68
5/14/2014	13.2	5.8	13	1.0	86183.27	424443.88	0.00	0.00	0.00
5/16/2014	20.1	3.0	20	1.0	36770.70	242274.37	0.00	0.00	0.00
5/19/2014	0.8	0.5	2	0.4	0.00	0.00	380736.22	0.00	0.00
6/4/2014	14.5	5.1	5	2.9	46568.71	14924.28	16376.42	0.00	16158.30
6/9/2014	25.1	11.4	7	3.6	6635.76	167282.56	57883.95	4483.24	22109.59
6/11/2014	16.0	8.4	12	1.3	4163.75	108201.57	5030.95	65924.35	6478.14
6/25/2014	6.6	4.8	6	1.1	3292.11	129990.28	56406.99	0.00	32423.55
7/7/2014	10.9	5.8	3	3.6	6339.96	16451.52	5532.97	0.00	17177.21
7/28/2014	20.3	10.9	5	4.1	15875.00	67922.09	33887.69	0.00	29721.82
7/31/2014	10.7	6.4	3	3.6	4740.54	14171.07	45526.85	0.00	28339.68
8/12/2014	15.5	11.9	8	1.9	10441.11	26203.22	94703.97	0.00	12019.40
8/20/2014	8.9	4.1	4	2.2	20634.48	33528.44	92255.31	0.00	6533.03
8/25/2014	6.6	3.0	5	1.3	14521.08	11701.58	117922.68	0.00	28690.75
8/27/2014	11.7	9.4	4	2.9	0.00		0.00	0.00	0.00
9/11/2014	20.3	5.8	14	1.5	151379.38	673721.47	534937.72	0.00	65326.11
9/17/2014	11.7	4.8	8	1.5	0.00	61092.45	111246.10	0.00	23894.99

Appendix B Sample dates with number of subsurface and surface samples collected

Sample Date	# subsurface samples	# surface samples
1/18/2013	25	--
2/14/2013	26	--
3/11/2013	29	--
3/22/2013	29	--
4/5/2013	27	--
4/17/2013	40	4
5/17/2013	7	--
5/20/2013	14	--
5/22/2013	15	--
5/24/2013	11	--
5/28/2013	10	5
5/31/2013	17	5
6/3/2013	25	5
6/5/2013	21	--
6/7/2013	16	--
6/10/2013	16	--
6/12/2013	14	--
6/14/2013	18	5
6/17/2013	16	--
6/19/2013	7	--
6/21/2013	6	--
6/24/2013	4	--
6/26/2013	1	5
6/28/2013	2	--
7/1/2013	1	1
7/5/2013	1	--
7/8/2013	6	4
7/11/2013	17	--
7/15/2013	5	--
7/18/2013	3	--
7/22/2013	3	5
7/25/2013	13	--
7/29/2013	4	--
8/1/2013	1	--
8/5/2013	11	--
8/8/2013	1	--
8/9/2013	16	5
8/12/2013	14	--
8/15/2013	3	--
8/19/2013	3	--
8/23/2013	2	--
8/26/2013	1	--
9/12/2013	--	4
9/20/2013	--	5
9/26/2013	5	--
10/7/2013	--	5
10/10/2013	15	--
10/23/2013	7	--

Sample Date	# subsurface samples	# surface samples
11/1/2013	--	4
11/20/2013	--	5
12/20/2013	--	5
2/20/2014	--	5
4/29/2014	--	3
5/6/2014	6	--
5/9/2014	5	--
5/12/2014	13	5
5/14/2014	13	4
5/16/2014	30	4
5/19/2014	33	1
5/21/2014	28	--
5/23/2014	28	--
5/28/2014	21	--
5/30/2014	17	--
6/2/2014	9	--
6/4/2014	7	4
6/6/2014	10	--
6/9/2014	13	5
6/11/2014	12	5
6/13/2014	10	--
6/16/2014	8	--
6/18/2014	28	--
6/20/2014	18	--
6/23/2014	16	--
6/25/2014	2	4
6/27/2014	2	--
7/2/2014	6	--
7/7/2014	3	2
7/10/2014	5	3
7/14/2014	1	4
7/17/2014	12	--
7/21/2014	5	--
7/24/2014	2	--
7/28/2014	3	4
7/30/2014	4	--
7/31/2014	--	4
8/12/2014	4	4
8/20/2014	7	4
8/25/2014	9	4
8/27/2014	12	4
9/11/2014	19	4
9/17/2014	28	4
9/22/2014	26	1
10/13/2014	--	4
10/16/2014	10	3
10/31/2014	35	5
11/10/2014	29	4

Appendix C Soil Analysis Results. A&L Laboratories (Fort Wayne, IN)

2011 TPAC East- assumed 0-10 cm composite samples												
crop	rep	N fert rate (kg/ha)	P fert rate (kg/ha)	K fert rate (kg/ha)	organic matter %	Bray-1 equiv. mg/g -P	mg/g-K	mg/g-Mg	mg/g-Ca	mg/g-Na	soil pH	Cation exchange capacity (meq/100g)
Miscanthus	1	50	0	0	2.7	54	120	345	2250		7.9	14.4
sorghum	1	150	0	0	4.0	53	164	375	1950		7.8	13.3
maize	1	150	0	0	2.8	55	134	375	1900		7.8	13.0
switchgrass	1	50	0	0	3.5	58	130	355	2550		7.8	16.0
poplar	1	0	0	0	2.9	50	128	365	2150		7.6	14.1
Miscanthus	2	50	0	0	3.2	41	101	360	1900		7.8	12.8
sorghum	2	150	0	0	3.9	40	126	355	1850		7.7	12.5
maize	2	150	0	0	2.8	40	123	375	1800		7.8	12.4
switchgrass	2	50	0	0	2.7	39	99	360	1800		7.8	12.3
poplar	2	0	0	0	3.9	46	133	345	1700		7.6	11.7
Miscanthus	3	50	0	0	2.8	17	74	320	2150		8.2	18.6
sorghum	3	150	0	0	2.6	19	67	335	220		8.1	14.0
maize	3	150	0	0	2.8	32	99	375	2100		7.9	13.9
switchgrass	3	50	0	0	3.6	26	87	340	2000		8.0	13.1
poplar	3	0	0	0	3.2	38	132	315	2300		7.9	14.5
Miscanthus	4	50	0	0	3.6	31	93	370	1900		7.7	12.8
sorghum	4	150	0	0	3.6	19	86	360	2300		7.9	14.7
maize	4	150	0	0	2.7	27	100	350	1800		7.5	12.2
switchgrass	4	50	0	0	3.3	48	172	320	2150		7.9	13.9
poplar	4	0	0	0	2.9	27	92	385	2000		7.8	13.4

2012 TPAC West- 0-10 cm												
crop	**rep**	**N fert rate (kg/ha)**	**P fert rate (kg/ha)**	**K fert rate (kg/ha)**	**organic matter %**	**Mahleich-3 mg/g-P**	**mg/g-K**	**mg/g-Mg**	**mg/g-Ca**	**mg/g-Na**	**soil pH**	**Cation exchange capacity (meq/100g)**
switchgrass	1	100	0	0	3.8	12	92	391	2083	14	6.2	16.4
switchgrass	1	0	0	0	3.8	133	88	339	1986	13	6.4	14.2
switchgrass	2	100	75	400	3.4	10	163	351	2112	10	6.4	15.1
switchgrass	2	0	75	400	3.4	9	139	312	1898	10	6.1	14.9
switchgrass	3	100	0	0	3.2	5	28	473	2204	15	6.8	15.7
switchgrass	3	0	0	0	3.0	6	106	422	1965	13	6.7	14.9
switchgrass	4	100	75	400	2.9	10	113	329	1707	1	6.1	14.0
switchgrass	4	0	75	400	3.1	9	114	360	1673	10	6.4	12.9
Miscanthus	1	100	0	0	3.5	9	33	409	2196	11	7.1	14.8
Miscanthus	1	0	0	0	3.3	10	112	284	1675	11	5.9	14.7
Miscanthus	2	100	0	0	3.1	6	134	449	2552	11	7.2	16.9
Miscanthus	2	0	30	300	3.9	39	473	272	2026	14	6.4	14.9
Miscanthus	3	0	0	0	3.5	12	135	394	2583	11	6.8	17.0
Miscanthus	3	100	30	300	4.1	62	483	303	2138	13	5.9	18.1
Miscanthus	4	100	30	300	4.4	54	499	343	2372	16	5.8	20.9
Miscanthus	4	0	30	300	4.4	38	469	336	2369	17	5.9	19.5
2012 TPAC West– 10-20 cm												
switchgrass	1	100	0	0	2.5	9	75	411	2174	16	6.5	15.8
switchgrass	1	0	0	0	2.7	11	69	358	2087	16	6.4	14.9
switchgrass	2	100	75	400	2.9	14	99	375	2213	13	6.1	18.1
switchgrass	2	0	75	400	2.8	13	85	359	2010	13	6.2	15.7
switchgrass	3	100	0	0	2.2	1	100	505	2072	16	6.7	16.1
switchgrass	3	0	0	0	2.3	1	100	459	1872	16	6.6	14.7
switchgrass	4	100	75	400	2.4	5	86	388	1655	12	6.4	13.0
switchgrass	4	0	75	400	2.1	3	105	476	2087	13	6.9	15.1
Miscanthus	1	100	0	0	2.3	5	98	408	2071	13	6.1	15.6
Miscanthus	1	0	0	0	2.2	6	85	278	1407	14	5.6	13.2
Miscanthus	2	100	0	0	2.1	1	86	369	1765	12	7.1	12.2
Miscanthus	2	0	30	300	2.7	11	92	315	2100	17	6.5	14.6
Miscanthus	3	0	0	0	2.7	9	82	315	2057	12	6.8	13.5
Miscanthus	3	100	30	300	2.9	26	97	270	1896	15	5.5	16.8
Miscanthus	4	100	30	300	2.8	21	121	337	2381	15	5.7	19.9
Miscanthus	4	0	30	300	3.1	15	114	350	2361	17	5.5	21.1