Potential of nitrogen management strategies to mitigate nitrous oxide emissions in corn

by

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Abstract

Effective management of nitrogen (N) in corn (*Zea mays* L.) cropping systems can positively affect production and mitigate environmental impacts such as nitrous (N_2O) emissions. The goal was to quantify N_2O emissions and the response of corn to application of N employing diverse management approaches (soil test and sensor-based approaches) to identify effective N management strategies. In 2016 and 2017, a corn study was established on a Belvue silt loam soil at the Ashland Bottoms Research Farm south of Manhattan, KS (39º 08’ N lat, 96º 37’ W long). In 2017, an additional site on a Eudora silt loam was added at the Kansas River Valley Experiment Field northwest of Topeka, KS (39º 04’ N lat, 95º 46’ W long). The study was a randomized complete block design comprised of five treatments replicated four times. Nitrogen treatments were stream applied as 28% N in the form of urea ammonium nitrate and included: Check, Soil Test, Split-Soil Test, Sensor, and Aerial NDVI. Nitrous oxide emissions were measured throughout the growing season using a static chamber method. Cumulative emissions ranged between 0.03 – 0.14 kg N_2O-N ha^{-1}. There were no significant differences among treatment cumulative emissions at any of the three site-years. Manhattan grain yields ranged from 6.2 – 11.3 and 1.9 – 6.7 Mg ha^{-1} in 2016 and 2017, respectively. Yield was not significantly across the four N management strategies in 2016, but in 2017 Split-Soil Test was significantly higher than Sensor. Topeka grain yields ranged from 8.0 – 15.2 Mg ha^{-1}. Soil Test and Split-Soil Test were significantly higher than Sensor and Aerial NDVI. Treatments receiving nitrogen yielded higher than the Check for all site-years. Yield-scaled nitrous oxide emissions (YSNE) were not significantly different at Manhattan in 2016 and Topeka in 2017. Check was significantly higher than the N management strategies at Manhattan in 2017. Emissions factor (EF) was ≥0.07 percent for all site-years on continuously tilled, low organic matter, river bottom silt loam soils with surface applied N fertilizer at agronomic N rates, which is markedly lower than the IPCC default value of one percent. Results between site-years were variable, which may stem from differences in site characteristics and water availability. Further investigation is needed to assess the ability of N management strategies to increase corn yield and lower N_2O emissions.

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Dedication

To all those along the way – thank you.

Chapter 1 - Literature Review

Background

In 1772, nitrogen was identified as an element and in the years following the nitrogen (N) cycle has been overwhelmingly moderated by humans (Galloway and Cowling, 2002). Exerting dominance on this biogeochemical cycle has been instrumental in supporting food and energy production. A consensus exists that fertilizer, including N sources, is responsible for 30 – 50 percent of all crop yields (Stewart et al., 2005). Stewart et al. (2005) reviewed multiple studies and found 30 – 50 percent may be a conservative estimate; because their review found that 40 – 60 percent of yield may be attributable to fertilizer. Furthermore, Stewart et al. (2005) found that fertilizer may bear greater responsibility for supporting yields in tropical environments than in temperate environments. One study that Stewart et al. (2005) reviewed was an irrigated 50-year continuous corn study located near Tribune, KS. This study found that N fertilizer raised yields 103 percent compared to the check plots receiving no N (Schlegel and Havlin, 2017). In the same study, plots receiving phosphorous fertilizer were 20 percent higher than the phosphorous check. When N and phosphorous were added together yields were 225 percent higher than plots receiving no fertilizer.

Corn yields continue to rise globally with roughly one percent of the world's corn on an area basis static (Ray et al., 2012). The number of hectares planted to corn in the United States was 38.0 and 36.5 million in 2016 and 2017, respectively (NASS, 2019). The average yield nationally was 11.0 Mg ha^{-1} in 2016 and 11.1 Mg ha^{-1} in 2017 (NASS, 2019). Kansas non-irrigated hectares were 1.4 and 1.6 million and yields were 7.6 and 6.7 Mg ha^{-1} in 2016 and 2017, respectively (NASS, 2019). Kansas irrigated hectares were 0.7 and 0.6 million and yields were 11.9 and 12.4 Mg ha^{-1} in 2016 and 2017, respectively (NASS, 2019). Yield trends in the

United States fall into one of two primary pools – stagnant and progressive increases (Ray et al., 2012). In the rainfed portions of the United States Corn Belt yields continue to increase faster than any other part of the world. However, approximately 26 percent of yields are stagnating globally, which in the United States corresponds largely to the irrigated portions of the Corn Belt. Similarly, a study found that irrigated yields did not increase from 2000 – 2008 (Grassini et al., 2011). A potential contribution to this stagnation is these irrigated environments typically exhibit fertilizer N efficiency 23 percent higher than the national average in corn. Overall, yield increases are accompanied by reduced county-level variability (Leng, 2017). Climate variability is strongly influential on yield variability. Nationally from 1980-1995 corn yield variability was 11 percent and decreased to 5 percent from 1995-2010. Rainfed environments tend to experience higher variability than irrigated environments. In areas of stagnation, such as irrigated portions of the Corn Belt, crop rotation, tillage, planting date, and seeding rate are the most influential management practices (Grassini et al., 2011). Although, these environments realize approximately 80 percent of yield potential and the aforementioned practices offer less than 13 percent yield increase. Additionally, the potential gain from enhanced management is overshadowed by fickle weather, higher input expenses, and overall greater risk in systems producing near yield potential.

Nitrogen uptake has also increased with yield, which is important given that 16 percent of N fertilizer is applied to corn globally (Ladha et al., 2016). Moreover, Landha et al. (2016) found fertilizer N represents 48 percent of plant N at harvest globally, which translates to 47 percent of fertilizer N applied. A study in Illinois evaluated corn hybrids from 1967 to 2006 and found that fertilizer N response was 0.16 kg grain kg^{-1} fertilizer N yr^{-1} (Haegele et al., 2013). Post-flowering N uptake appears to be a principal force behind increased fertilizer response. The plant's ability to assimilate mineralized N from the soil was static during this time. Yield improvement at low N accounts for approximately two-thirds of yield improvement compared to high N yields, which suggests much of the corn yield improvement does not stem from selection for high N response. Haegele et al. (2013) argues that in order to meet future demands selection for high N response must occur moving forward.

In addition to genetic gain, N rates have increased during the past few decades (Ladha et al., 2016). During this time, management practices have evolved and offered enhanced management opportunities; however, producer adoption of best management practices remains low (Weber and McCann, 2014). A 2010 survey of 1840 corn producers in the United States found that 21, three, and ten percent utilized soil tests, plant tissue analysis, and N inhibitors, respectively. The information source from which the producer received their information, was a strong determinant of best management practice adoption. Producers receiving information from fertilizer dealers were less likely to soil or tissue test. A producer's farm philosophy may influence N management practices; because those that implemented conservation tillage had a higher adoption of tissue testing and N inhibitors. Likewise, producers receiving conservation funding had an increased likelihood of using soil and tissue tests. While enhanced management tools and insights will offer immense opportunities to steward N it will be in vain if producers fail to adopt best management practices.

Nitrogen has, is, and will play an indisputably important role in supporting the global food system and will continue to do so in the face of a growing population and a changing climate (Godfray, 2014). Moreover, the role of N in intensified cropping systems must be understood as agricultural extensification is not a viable option to support a growing global population due to concerns of preserving biodiversity (Godfray et al., 2010). Producers, agronomists, scientists, and policy-makers will be held accountable for ensuring the responsible stewardship of N leading to 2050, which will be a time of agroecosystem intensification (Galloway and Cowling, 2002; Godfray et al., 2010; Godfray, 2014). Woli et al. (2016) found that modern corn hybrids recovered 51 – 88 percent of N applied. Nitrogen Recovery Efficiency generally was inversely related N application rate. Low nutrient use efficiency poses a direct issue regarding environmental contamination as humans have raised N levels in environmental reservoirs including aquatic ecosystems and the atmosphere (Galloway and Cowling, 2002). Terrestrial, aquatic and atmospheric environments are interconnected, thus changing the amount of N in one environment causes an imbalance that can induce change in the other pools of N. Inefficient nutrient use poses an indirect environmental concern due to fossil fuel consumption and greenhouse gases associated with synthetic fertilizer production. Quantifying the N cycle to understand the rate of additions and losses from N reservoirs will be a critical step in understanding and mitigating environmental damage, which is not a trivial task given nitrogen's dynamic nature (Galloway and Cowling, 2002).

Nitrogen Cycle

Nitrogen is continually cycling through the soil, plants, and atmosphere. In order to manage N properly, it is important to understand what factors influence the N cycle. This section will review N in the principal pools: the atmosphere, plant tissue, and soil.

Nitrogen in the atmosphere primarily exists as N gas (N_2), which is an inert gas. Approximately 99.3840 percent of N in the soil-plant/animal-atmosphere system exists in the atmosphere (Havlin et al., 2014). Other nitrogenous compounds, such as nitrous oxide (N_2O), are present in the atmosphere but at trace levels. However, the lack of abundance should not discount the importance of trace gases. For example, N_2O has a CO_2 equivalent of 298 over a

100-yr period (Forster et al.,2007), thus N_2O is 298 stronger than CO_2 on a mass basis. The GHG potential of N_2O makes a large concern in the overall GHG budget.

Nitrogen also resides in plants. It is a key constituent in amino acids, chlorophyll, proteins and many other compounds essential to plant life (Taiz et al, 2015). How plants acquire N varies based on the type of plant (Havlin et al, 2014). Non-leguminous plants depend on the soil to supply all their N. Nitrate and ammonium are the two inorganic forms of N that are bioavailable. The majority of N is brought to the plant via mass flow, which means the N moves through the soil profile with water. Leguminous plants have formed a symbiotic relationship with select bacteria that are able to convert N_2 to ammonium. This symbiotic relationship is known as biological N fixation. In exchange for N, the nitrogen-fixing bacteria receive energy from the plant. Legumes receive only part of their N from the bacteria while the soil furnishes the balance of the plants N requirement.

Three general processes characterize the soil N cycle: additions, transformations, and losses. Soil N exists in two primary pools: organic and inorganic (Scharf, 2015). Organic N is the larger pool and contains carbon along with the N in a molecule, whereas inorganic lacks carbon in a molecule. Because a N source enters the cropping system as organic or inorganic does not mean it will reside permanently in that pool.

Nitrogen can be added to the cropping system via biological N fixation, addition of organic material, or synthetic fertilizer (Havlin et al., 2014). Crop residue and manure are examples of common organic N sources. In addition, these sources may contain some inorganic N that is immediately available to the plant, but the organic N must undergo a transformation to inorganic before it is available to the plant. In cropping systems N commonly is added through synthetic fertilizer, which is often in inorganic form and immediately available to the plant.

Nitrogen is not static and can cycle between organic and inorganic. Transformation of N from organic to inorganic and vice versa is facilitated by soil microbes. The process of transforming inorganic N to organic form is known as immobilization. Conversely, organic to inorganic is known as mineralization. Whether an organic N source added to the cropping system will remain organic or undergo mineralization largely depends on its carbon to N ratio. Generally, sources with a ratio ≥20:1 will remain in organic form, whereas sources with a ratio ≤20:1 will be mineralized to ammonium. Soil microbes must maintain a certain C:N ratio and as they consume compounds containing organic N they are only able to use so much of the carbon and the remainder is respired. If there is more N than necessary to maintain a proper C:N ratio for the carbon that was not respired then mineralization to ammonium occurs. Ammonium can undergo transformation into nitrate, which is known as nitrification. Nitrification is a two-step process: (i) ammonium in converted to nitrite; (ii) nitrite is converted to nitrate. Both steps of nitrification are facilitated by bacteria.

An additional loss pathway is ammonia volatilization. Some producers supplement their soil N with anhydrous ammonia. Ammonia is susceptible to loss via ammonia volatilization. The chemical reaction is depicted below:

$$NH_{4}{}^{+}_{(aq)} + OH^{-}_{(aq)} \leftrightarrow NH_{3}{}_{(g)} + H_2O_{(l)}$$

Equation 1.1 Reaction of ammonium in water.

Ammonium and hydroxide are in equilibrium with ammonia and water in soil solution. When there are additions of ammonium and it is transformed to ammonia, it is susceptible to gaseous loss. This phenomenon is compounded in high pH due to a higher concentration of hydroxide ions (Sommer et al., 2004). Urea that is surface applied and not incorporated is also susceptible to ammonia volatilization (Scharf, 2015).

Nitrification is a process that transforms oxidized ammonium into nitrate. Nitrate is an anion unlike ammonium, which is a cation. Ammonium will adsorb to the cation exchange sites on clay particles or be fixed by clay minerals, however nitrate remains in soil solution (Havlin et al., 2014). Since nitrate does not adsorb to clay particles it is susceptible to leaching. Leaching occurs when water accompanied by nitrate moves downward and eventually exits the soil profile. When nitrate exits the cropping system via leaching it can lead to increased nitrate concentration in groundwater and eutrophication of surface waters can occur. In addition to leaching, nitrate in the soil profile and waterways is prone to denitrification (Rivett et al., 2008).

Denitrification

Complete denitrification results in the generation of N_2. However, if the stepwise reaction that is primarily facilitated by soil microbes is interrupted prior to the generation of N_2, N_2O can result. In addition to N gas and nitrous oxide, nitrite (NO_2^-) and nitric oxide (NO) can result from denitrification (Aulakh et al., 1992). Denitrification is detailed in the following equation:

$$NO_3^-{}_{(aq)} \rightarrow NO_2^-{}_{(aq)} \rightarrow NO_{(g)} \rightarrow N_2O_{(g)} \rightarrow N_{2(g)}$$

Equation 1.2 Reduction of nitrate via denitrification.

Nitrous oxide has a global warming potential 298 times stronger than carbon dioxide on a mass basis over a 100-yr time period, which makes it of particular interest (Forster et al., 2007). N_2O is important to agriculture for two primary reasons: N_2O is a potent greenhouse gas (GHG) and the largest component of the agricultural GHG budget (Venterea et al., 2012). In 2016, agriculture accounted for approximately 9 percent of all GHG emissions in the United States (US EPA, 2019). Nitrous oxide resulting from soil management accounted for approximately 4.5 percent of total emissions, or just under half of all agricultural emissions. Furthermore, the N_2O may give rise to a positive feedback cycle as N_2O production in the United State Corn Belt is expected to increase under warmer and wetter conditions due to climate change (Griffis et al., 2017).

A challenge in forecasting and managing for N_2O losses is the unpredictability of N_2O. Many factors contribute to the loss of N as N_2O including soil texture, drainage, water-filled pore space, soil N, organic carbon, soil pH, temperature, and soil microbes present. Soil metrics partially explain N_2O; however, to fully understand N_2O dynamics management must be integrated into the analysis which will be discussed later in the chapter.

Soil moisture is a key determinant in N_2O production. Water-filled pore space (WFPS) is a term frequently used in the literature pertaining to N_2O, because it provides a means to compare soils that may have different water holding capacities. The WFPS is the average soil pore space occupied by water and is presented as a percentage. A study found that WFPS determines N_2O output when temperature and nitrate are not limiting factors (Sehy et al., 2003). In general, N_2O has a positive response to increasing WFPS. Part of the response to WFPS is attributable to aerobic and anaerobic soil microbes (Linn and Doran, 1984a; Weier et al., 1993). Sixty percent WFPS has been identified as a threshold for N_2O production and N_2O will continue to increase beyond 60 percent WFPS (Sehy et al., 2003). However, Davidson (1991) found that peak N_2O emissions occur between 50 – 80 percent WFPS.

Soil N availability or concentration play an important role in the amount of N_2O production. Multiple studies have found that N_2O increases exponentially in response to increasing soil N (Hoben et al., 2011; Kim et al., 2013; Shcherbak et al., 2014). This effect is amplified when N levels surpass plant demand (Shcherbak et al., 2014). A study conducted in Michigan featuring a wheat, corn, soybean rotation found that inorganic N availability may increase as a result of climate change, thereby promoting N_2O (Ruan and Robertson, 2017). As climate change progresses the prevalence of snow cover is expected to decline, which is apt to increase soil freeze-thaw cycles. Ruan and Robertson (2017) found that areas with ambient snow cover and additional snow beyond ambient snow cover resulted in 41 and 49 percent lower cumulative N_2O than no snow cover, respectively. This is partially attributable to the physical degradation of macroaggregates from freeze-thaw cycles that resulted in higher soil nitrate.

Soil carbon also underpins denitrification (Weier et al., 1993; Bouwman et al., 2002; Mosier et al., 2002; Senbayram et al., 2012; Shcherbak et al., 2014). Weier et al. (1993) found that the addition of carbon when soil conditions are conducive to denitrification lead to a greater ratio of N_2O to N_2. However, in soils with low nitrate levels, the addition of carbon may result in lower N_2O to N_2 (Senbayram et al., 2012). The importance of carbon stems from its role in regulating oxygen levels in soil (Mosier et al., 2002). Generally increasing soil carbon lends itself to higher N_2O emissions (Weier et al., 1993; Bouwman et al., 2002). Shcherbak et al. (2014) found that 1.5 percent soil carbon is a threshold for higher N_2O emissions However, one study found that high soil carbon lowered N_2O emissions in the presence of low nitrate, but high soil carbon elevated N_2O emissions at high nitrate levels (Linn and Doran, 1984a).

Lastly, soil pH contributes to the production of N_2O. Neutral to acidic soil pH is conducive to N_2O emissions (Bouwman et al., 2002; Shcherbak et al., 2014). With many factors contributing to N_2O emissions, it is difficult to forecast with accuracy the magnitude of emissions for a cropping system. The fickleness of N_2O demands a systems approach to manage emissions in the field.

4R Nutrient Stewardship

In the late 1980’s and early 1990’s scientists with Potash & Phosphate Institute (PPI), now known as the International Plant Nutrition Institute (IPNI), were defining best management practices (BMPs) for fertilizer stewardship (Roberts, 2007). This work set the stage for the development of The Global “4R” Nutrient Stewardship Framework. The “4R” framework emphasizes the right source, right rate, right time, and right place. These four elements together address the social, environmental, and economic demands pertaining to plant nutrients in the cropping system (Johnston and Bruulsema, 2014). Implementing the “4R” framework provides a viable option to mitigate N_2O emissions (Venterea et al., 2016).

Right Source

Producers have many nutrient source options, such as synthetic fertilizer, animal manure, biosolids, etc. Nitrogen source has a strong influence on N_2O emissions. Urea and poultry litter can lend themselves to higher N_2O emissions (Sistani et al., 2011; Halvorson and Del Grosso, 2013). Sistani et al. attribute the increased N_2O emissions from poultry litter to the carbon that accompanies the N. Enhanced efficiency fertilizers including polymer-coated urea, urea and urea ammonium nitrate (UAN) paired with urease and nitrification inhibitors frequently result in lower N_2O emissions and have not been found to increase N_2O emissions under any conditions (Halvorson et al., 2011; Halvorson and Del Grosso, 2012; Burzaco et al., 2013; Maharjan and Venterea, 2013; Maharjan et al., 2014; Eagle et al., 2017). Urease and nitrification inhibitors consistently lowered N_2O emissions, whereas the benefits of polymer-coated urea were realized in warm and wet growing conditions (Maharjan and Venterea, 2013; Fernández et al., 2015). The reported emissions reductions for nitrification inhibitors alone and urease/nitrification inhibitors combined range between 10 and 31 percent (Burzaco et al., 2013; Abalos et al., 2016; Eagle et al., 2017). Additionally, enhanced efficiency fertilizers maintained or improved yield (Halvorson et al., 2010, 2011; Sistani et al., 2011; Halvorson and Del Grosso, 2012, 2013; Burzaco et al., 2014; Halvorson and Bartolo, 2014; Fernández et al., 2016). Maintained or enhanced yields coupled with a reduction in N_2O has a complementary effect on lowering yield-scaled N_2O.

Right Rate

Determining the appropriate rate of N has been an ongoing problem for agronomists, researchers, and producers. N is very dynamic and susceptible to loss leading producers to over apply N to avoid yield reduction (Roberts et al., 2010). Exceeding the agronomic optimum N rate can lead to disproportionate increases in N_2O (Ma et al., 2010; Eagle et al., 2017). Methods to predict N demand and place the proper amount of N, such as soil testing and tissue testing have existed for some time, but frequently fall short in accuracy and precision (Morris et al., 2018). Maximum Return To Nitrogen (MRTN) addresses N application rates by accounting for plant response to N and the cost per unit of N to optimize economic return of N. MRTN may present an opportunity to balance profitability while simultaneously lowering N_2O emissions upwards of 50 percent (Millar et al., 2010). Again, MRTN performance, as with soil and tissue testing has a large margin for improvement (Morris et al., 2018). A common theme in the aforementioned approaches was the inability to account for the variability that can occur in the growing season largely due to weather. Sensors and dynamic models offer potential N rate solutions that account for in-season variability. The ability of crop sensors to detect N deficiency/sufficiency has been inconsistent. Studies have shown that sensors are capable of detecting N deficiency (Ruiz Diaz et al., 2008; Barker and Sawyer, 2010). Although sensors have failed to properly diagnose N status (Barker and Sawyer, 2017). A challenge exists for crop sensors as plant N approaches deficiency/sufficiency threshold as the sensor may not be able to distinguish hidden hunger from sufficiency (Barker and Sawyer, 2010). Algorithms that produce recommendations based on sensor data provide additional challenges including dependency on a specific sensor model, incompatibility among geographies, and inability to account for previous N applications (Bean et al., 2018). Dynamic crop models eliminate some voids found in crop sensors, such as being able to integrate weather data, soil characteristics, previous N application, etc. Dynamic models have outperformed static N recommendations tools in predicting the economically optimum N rate (Sela et al., 2017). However, dynamic models may provide liberal recommendations compared to crop sensors (Thompson et al., 2015). Integrating crop sensor data into dynamic models may establish a synergy that provides greater accuracy and precision in predicting optimum N rate.

Right Time

Timing of nutrient application is a key factor in managing N_2O. A Canadian model-based analysis supported by field validation found that in a corn cropping system fall application (i.e. fall anhydrous ammonia) is favorable for increased N_2O (Abalos et al., 2016). In part, the observations from Abalos et al. (2016) may be explained by the release of ammonium from freeze-thaw cycles as noted in Ruan and Robertson (2017). Results are not as clear with spring pre-plant and in-season applications. A tenet of the “4R” framework is matching application timing to crop demand, suggesting that split-application or side-dress treatments would be advantageous over pre-plant N due to increasing nutrient uptake from the plant later in the growing season. Some studies confirm this extension that split or side-dress application will reduce N_2O (Abalos et al., 2016; Fernández et al., 2016; Eagle et al., 2017). This may be attributable to synchronization with crop demand; however, reduction potential appears to be site-specific. Other studies demonstrated split or side-dress application can increase N_2O (Ma et al., 2010; Burzaco et al., 2013; Venterea and Coulter, 2015). Ma et al. (2010) evaluated N rate and timing in a Canada corn system, and observed that side-dress N_2O emissions were higher than pre-plant application ($P=0.07$). Burzaco et al. (2014) found that side-dress application in corn compared to pre-plant N application raised cumulative emissions 28 percent, which was likely attributable to water filled pore space observed being above 60 percent. Similarly, Venterea and Coulter (2015), found that in a wet year that split-application in corn significantly increased emissions over pre-plant application; however, across all site-year timing was not significant. These studies suggest that weather may contribute considerably to the success or lack thereof for a particular timing. Warm and wet conditions proximal in time to application can undermine the success of timing BMPs, such as side-dress or split-application.

Right Place

The final element of the "4R" framework is place. Placement of the nutrient source has considerable implications for N_2O emissions. Banding fertilizer is often revered as a BMP for fertilizer application, but banding can result in higher N_2O emissions (Halvorson and Del Grosso, 2013; Eagle et al., 2017). Halvorson and Del Grosso (2013) found that surface banding increased N_2O emissions per kg of N applied were 59 percent from broadcast in an irrigated Colorado corn system. Similarly, a meta-analysis from Eagle et al. (2017) discovered that broadcasting might lower N_2O emissions between 23 and 31 percent in corn cropping systems. The effect of placement can be difficult to discern as it is often confounded with time and source. Soil metrics, such as temperature, moisture, and N concentration in the application vicinity may influence the differences observed between various placements. Further research is needed to determine the effects of placement and what cropping system factors influence N_2O production with respect to placement.

Corn Production and N_2O

A study published in 2012 found that the US corn belt produced 0.9 – 1.2 Tg N_2O-N annually (Miller et al., 2012). Based on the group's findings, Miller et al. (2012) estimated that total US and Canada N_2O emissions were between 2.1 – 2.6 Tg N_2O-N per year, which would account for 12 – 15 percent of all N_2O emissions or 32 – 39 percent of emissions globally. Additionally, Miller et al. (2012) found that N_2O emissions were acutely seasonal and strongly correlated to side-dress N applications in corn.

Studies conducted on a local scale suggest that stewardship beyond the scope of the "4Rs" may be necessary to mitigate N_2O production. A study conducted in Indiana evaluated weather, N source, and crop rotation (Hernandez-Ramirez et al., 2009). Cumulative N_2O-N emissions from early Spring to late Fall were between 3.0 and 8.0 kg N_2O-N ha^{-1}. Rainfall events that occurred close to nutrient application were largely responsible for differences in nutrient source, because nutrient sources had different application timings. Soil temperature was also a driver of N_2O emissions. Beyond the "4Rs" researchers found that switching from a corn-corn rotation to a corn-soybean rotation was a viable means to reduce N_2O-N. Lastly, the authors reported that returning production land to prairie would lower N_2O; however, this is unlikely to be adopted by producers and landowners.

A 20-yr study in southwest Michigan compared four annual cropping systems, three perennial cropping systems, and four ecosystems without direct anthropogenic influence (Shcherbak et al., 2016). The four annual cropping systems consisted of a corn-soybean-wheat rotation but were subject to conventional, no-till, reduced input, and biologically based management strategies. Cumulative emissions, yield-scaled emissions, and emissions factor were determined for all systems. Cumulative emissions averaged across all 20 years were between 0.74 – 1.36 kg N_2O-N ha^{-1} yr^{-1} for corn with significant differences among management systems; however, cumulative emissions for the entire rotation were not different among management strategies. Yield-scaled corn N_2O-N averages varied 0.102 – 0.165 kg N_2O-N Mg^{-1} grain, but no significant differences were observed. Likewise, emissions factor averages for corn ranged from 0.77 to 1.33 percent with no significant differences.

Studies assessing management practices beyond the scope of nutrient management have generated mixed results. A study in Iowa found that in a corn-soybean rotation, corn cumulative N_2O emissions averaged 7.6 – 10.2 kg N_2O-N ha^{-1} yr^{-1}; however, emissions were not significantly influenced by tillage or cover crop (Parkin and Kaspar, 2006). Likewise, a long-term study in Michigan found no significant difference between no-till and tillage (Grandy et al., 2006). In contrast, a long-term study in Indiana investigating the effect of tillage and crop rotation found that no-till lowered N_2O emissions 40 percent compared to moldboard plowing and 57 percent compared to chisel plowing (Omonode et al., 2010). Furthermore, the study found that a corn-soybean rotation lowered N_2O emissions by 20 percent in corn compared to continuous corn. A separate study in Canada found a significant interaction between tillage and N placement (Drury et al., 2006). Tillage included no-till, zone, and moldboard, as well as N placement consisting of shallow and deep. Zone-tillage couple with shallow N placement had the greatest reduction in emissions.

Summary

A challenge with delineating the effects of individual management practices is they often confound one another. Meta-analyses encompassing many data sets present unique opportunities for improving the understanding of individual elements to manage N_2O. Furthermore, modifying an element of the “4R” framework is insufficient to reduce N_2O. Multiple elements of the framework must be combined in order to provide realistic mitigation (Venterea et al., 2016). It is reasonable to assert that measures must go beyond the “4R” framework to gain traction in reducing N_2O. Additional research is needed to elucidate the impacts of tillage as the current data are inconsistent (Linn and Doran, 1984b; a; Ussiri et al., 2009; Drury et al., 2012). Further research is needed on the impacts of crop rotation. Continuous corn is favorable for N_2O emissions, but more data are needed to quantify the effects of crop rotation (Drury et al., 2008). Researchers may need to consider what are the critical parameters when studying N_2O. Many studies fail to mention nitrite, which may explain up to 44 percent of N_2O variability (Maharjan and Venterea, 2013). Lastly, current approaches emphasize direct N_2O emissions from the cropping system. A study estimated that indirect N_2O emissions, emissions that occurred from nitrate leaching, were 79 – 117 percent of direct emissions, therefore it is important that future research comprehensively addresses all N loss mechanisms and management strategies are tailored accordingly (Maharjan et al., 2014). There is not a simple antidote for managing N_2O emissions. Successful mitigation will require a systems approach supported by comprehensive research.

Hypothesis and Objectives for Research

The hypotheses of this project were: (i) increasing fertilizer N rates would result in increasing corn yield and recommendation strategies with the highest N rate would maximize yield; (ii) there would be a corresponding increase in N_2O emissions with increasing N applied; (iii) a recommendation strategy that minimized N rate without compromising yield would result in the lowest yield-scaled N_2O emissions. The objectives of this study were to (i) assess the ability of N recommendation strategies to optimize corn yield; (ii) determine the potential of N recommendation strategies to lower N_2O; (iii) identify the strategy with the greatest potential to minimize yield-scaled emissions.

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Chapter 2 - Nitrous Oxide Emissions from Corn Grown on Kansas Silt Loam Low Organic Matter Soils

Abstract

Effective management of nitrogen (N) in corn (*Zea mays* L.) cropping systems can positively affect production and mitigate environmental impacts such as nitrous (N_2O) emissions. The goal was to quantify N_2O emissions and the response of corn to application of N employing diverse management approaches (soil test and sensor-based approaches) to identify effective N management strategies. In 2016 and 2017, a corn study was established on a Belvue silt loam soil at the Ashland Bottoms Research Farm south of Manhattan, KS (39º 08' N lat, 96º 37' W long). In 2017, an additional site on a Eudora silt loam was added at the Kansas River Valley Experiment Field northwest of Topeka, KS (39º 04' N lat, 95º 46' W long). The study was a randomized complete block design comprised of five treatments replicated four times. Nitrogen treatments were stream applied as 28% N in the form of urea ammonium nitrate and included: Check, Soil Test, Split-Soil Test, Sensor, and Aerial NDVI. Nitrous oxide emissions were measured throughout the growing season using a static chamber method. Cumulative emissions ranged between 0.03 – 0.14 kg N_2O-N ha^{-1}. There were no significant differences among treatment cumulative emissions at any of the three site-years. Manhattan grain yields ranged from 6.2 – 11.3 and 1.9 – 6.7 Mg ha^{-1} in 2016 and 2017, respectively. Yield was not significantly different across the four N management strategies in 2016, but in 2017 Split-Soil Test was significantly higher than Sensor. Topeka grain yields ranged from 8.0 – 15.2 Mg ha^{-1}. Soil Test and Split-Soil Test were significantly higher than Sensor and Aerial NDVI. Treatments receiving nitrogen yielded higher than the Check for all site-years. Yield-scaled nitrous oxide emissions (YSNE) were not significantly different at Manhattan in 2016 and Topeka in 2017. Check was

significantly higher than the N management strategies at Manhattan in 2017. Emissions factor (EF) was ≥0.07 percent for all site-years on continuously tilled, low organic matter, river bottom silt loam soils with surface applied N fertilizer at agronomic N rates, which is markedly lower than the IPCC default value of one percent. Results between site-years were variable, which may stem from differences in site characteristics and water availability. Further investigation is needed to assess the ability of N management strategies to increase corn yield and lower N_2O emissions.

Key Findings

- N influence on N_2O and yield vary between corn growing environments.
- Optimal N management strategy may differ between irrigated and dryland systems.
- IPCC EF of 1 percent may overestimate N_2O emissions.

Introduction

A conservative estimate is that 30 – 50 percent of crop yields result from fertilizer application (Stewart et al., 2005). Woli et al. (2016) found that only 51 – 88 percent of N applied was recovered by the corn crop, which translates to a 12 – 49 percent loss of fertilizer applied. Such low efficiency is undesirable due to economic costs, agronomic limitations and environmental concerns. The lack of efficiency is not due to lack of effort. The N cycle has been anthropogenically driven in recent history, which has played an instrumental role in supporting food and energy production (Galloway and Cowling, 2002). The role of N is apt to increase in prominence in the face of a growing population and climate change (Godfray, 2014). Agricultural extensification is not a viable option without adversely impacting biodiversity, therefore intensification must occur (Godfray et al., 2010). Nitrogen will serve a critical role in agroecosystem intensification with producers, agronomists, scientists and policy-makers accountable for the proper stewardship of this nutrient (Galloway and Cowling, 2002; Godfray et al., 2010; Godfray, 2014).

Developing a deeper quantitative understanding of the N cycle and how management influences the cycle will be crucial for better stewardship and reduced environmental burden (Galloway and Cowling, 2002). Nitrous oxide is a focal point in advancing N stewardship due to its dynamic nature and GHG potential. N_2O is the largest component of the agricultural GHG budget and has a CO_2 equivalent of 298 (Forster et al., 2007; Venterea et al., 2012). Furthermore, a positive feedback cycle may exist as climate change is expected to increase US Corn Belt N_2O emissions stemming from a wetter and warmer climate with increased soil mineral N (Griffis et al., 2017; Ruan and Robertson, 2017).

The International Plant Nutrition Institute (IPNI) has established The Global “4R” Nutrient Stewardship Framework, which emphasizes the Right Source, Right Rate, Right Time and Right Place for fertilizer application (Roberts, 2007). Venterea et al. (2016) found that one component of the “4R” framework was insufficient to manage N_2O, but combining multiple components lowered N_2O emissions. This study will focus on the Right Rate and Right Time. Right Rate is critical in mitigating N_2O emissions as studies have shown that N_2O response to increasing soil N, particularly when soil N exceeds plant demand, is exponential (Ma et al., 2010; Hoben et al., 2011; Kim et al., 2013; Shcherbak et al., 2014; Eagle et al., 2017). Farmers will inadvertently over-apply N to avoid a yield reduction (Roberts et al., 2010). Soil testing has been the standard for recommending N but provides inconsistent results (Morris et al., 2018). Sensors and models offer new opportunities in prescribing the proper rate of N; however, more information is needed regarding performance across geographies and environments (Ruiz Diaz et al., 2008; Barker and Sawyer, 2010; Sela et al., 2017).

Additionally, the Right Time provides the opportunity to synchronize N application with plant demand limiting the amount of time N is prone to loss. Currently, data surrounding pre-plant versus in-season N applications and potential N_2O emissions are inconclusive (Ma et al., 2010; Burzaco et al., 2013; Venterea and Coulter, 2015; Abalos et al., 2016; Fernández et al., 2016; Eagle et al., 2017). Ma et al. (2010), Abalos et al. (2016), Fernandez et al. (2016), and Eagle et al. (2017) found significant reductions in cumulative emissions and/or yield-scaled nitrous oxide emissions (YSNE) with split or side-dress applications compared to pre-plant. Burzaco et al. (2013) and Venterea and Coulter (2015) found significant increases in cumulative and/or YSNE with side-dress and split applications. Efficacy of timing appears to hinge largely on weather conditions near the time of application. Increased cumulative emissions and/or YSNE resulted from heavy precipitation coinciding with split and side-dress timings. This would be consistent with increased WFPS resulting in increased N_2O in the presence of abundant N (Weier et al., 1993; Sehy et al., 2003; Griffis et al., 2017). Additionally, side-dress and split timings often coincide with warmer soil temperatures, which have been shown to increase N_2O (Sehy et al., 2003; Griffis et al., 2017).

Many studies have focused on N recommendation strategies to optimize yield. Other studies have observed the effects of N rate on N_2O emissions. A study in Michigan found that yield did not significantly increase beyond the optimum economic N rate; however, N_2O emissions increased exponentially when optimum economic N rate was exceeded (Hoben et al., 2011). Similarly, a meta-analysis of 22 studies found that in 18 studies there was an exponential increase in N_2O emissions in response to increasing N rate (Kim et al., 2013), thus suggesting that reductions in N_2O can be made by accurately determining crop N needs and preventing over application of N. Few studies have assessed N management strategies encompassing the Right

Rate and Right Time to balance yield and N_2O emissions. The objective of this study was to assess four N management strategies for potential to optimize corn (*Zea mays*) yield and reduce N_2O emissions. The hypotheses were: (i) increasing N rates would result in increasing corn yield and recommendation strategies with the highest N rate would maximize yield; (ii) there would be a corresponding increase in N_2O emissions with increasing N applied; (iii) a recommendation strategy that minimized N rate without compromising yield would result in the lowest yield-scaled N_2O emissions.

Materials and Methods

Site Description and Experimental Design

This study was located at the Kansas State University Ashland Bottoms Agronomy Farm, Manhattan, KS in 2016 and 2017 and at the Kansas River Valley Experiment Field, Topeka, KS in 2017. The Ashland Bottoms Agronomy Farm (Manhattan) is located 39˚ 08’ N 96˚ 37’ W at an approximate elevation of 312 m. The site was dryland and subject to conventional tillage. Soil type was a Belvue silt loam, coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvent. The Belvue silt loam Ap_1 sub-horizon contained 6.6, 42.9, and 50.5 percent clay, silt, and sand, respectively (NCSS, 2019). The 30-yr average annual precipitation was 828 mm with January being the driest month (17 mm) and June being the wettest month (129 mm). The Kansas River Valley Experiment Field (Topeka), is located 39˚ 04’ N 95˚ 46’ W at an approximate elevation of 270 m. The site was irrigated and managed with conventional tillage. The soil type was a Eudora silt loam, coarse-silty, mixed, superactive, mesic Fluventic Hapludoll. The Ap_1 sub-horizon contained 11.5, 52.6, and 35.9 percent clay, silt, and sand, respectively (NCSS, 2019). Annual 30-yr average precipitation was 926 mm with lowest monthly precipitation in January (22 mm) and highest monthly precipitation in June (137 mm). According to the Köppen Climate

Classification System, both sites were Cfa, characterized as warm temperate, fully humid, hot summer. Early season nutrient values for all three site-years can be found in Table 2.1.

The experimental design at both sites was a complete randomized block design with a one-way treatment structure. Each site consisted of four blocks with five treatments per block. Treatments were Check, Soil Test, Split-Soil Test, Sensor, and Aerial NDVI (Table 2.2). Check received no N and served to determine baseline N_2O emissions and yield. Soil Test and Split-Soil Test N application rates (Table 2.2) were based on Kansas State University pre-plant N recommendation (Leikam et al., 2003). Yield goal was the anticipated yield ahead of the growing season as determined by the research group. The yield goal for Manhattan in 2016 and 2017 was 3.8 Mg ha^{-1}. In Topeka the yield goal was 5.1 Mg ha^{-1}. The Sensor N application rate (Table 2.2) was based on NDVI readings from the Trimble GreenSeeker handheld (Trimble, Sunnyvale, CA). Aerial NDVI N application rate (Table 2.2) was based on NDVI reading from the RedEdgeMX sensor (MicaSense, Seattle, WA) mounted on an unmanned aerial vehicle. Nitrogen recommendations from Sensor and Aerial NDVI were based on the corn N algorithm described by Asebedo (2015). Nitrogen applications of 28% UAN were made using an all-terrain vehicle with a sprayer featuring an appropriate streamer nozzle for the application volume.

The plots were 6.10 m wide and 21.33 m long with four rows spaced 0.76 m apart. Pioneer 1151 (DowDuPont, Midland, MI) served as the corn hybrid with a target planting population of 69,000 and 89,000 seeds ha^{-1} at Manhattan and Topeka, respectively. Manhattan was planted 22 and 21 April and harvested on 29 and 26 September in 2016 and 2017, respectively. Topeka was planted 24 April and harvested 19 September.

Soil Nitrous Oxide Emissions Measurements and Calculations

Nitrous oxide was measured using the static chamber method described in the USDA GRACEnet Project Protocols (Parkin and Venterea, 2010). Chambers were centered over the fourth row 4.6 m from the front of the plot. Polyvinylchloride (PVC) chambers consisted of two primary components: an anchor that resided in the plot throughout the duration of the growing season and a lid that sealed to the anchor during sampling. The anchor was 30.3 cm in diameter and 15 cm long with a beveled edge on the bottom to ease insertion into soil. Anchors were inserted 9 cm into the soil with 6 cm exposed above the soil surface (Parkin and Venterea, 2010). The lid was 30.3 cm in diameter and 10 cm long. Mylar reflective tape encased the lid to mitigate the influence of solar radiation on chamber temperature during sampling. A temperature probe was inserted through a rubber stopper on the lid to record the internal temperature of the chamber during sampling. A replaceable butyl rubber septum was located at the top of the lid to extract samples (Labco Ltd., Lampeter, Wales). A small vent was located on the side of the lid. Additionally, a 10.2 cm section of rubber inner tube was fastened to the bottom of the lid, which secured and sealed the lid to the anchor during sampling.

Generally, sampling occurred between 0600 and 1300 h. A block was sampled simultaneously over the course of 45 min. 20 mL was extracted from the chamber using a 30 mL syringe at 0, 15, 30, and 45 min and placed into an empty 12 mL borosilicate vial for each time interval, which had 30 mL evacuated from the vial prior to sampling. Samples remained in vials until analysis by gas chromatography as described by Wilson et al. (2015) to determine N_2O. A Varian 450-GC with an electron capture detector (ECD) (standard deviation of ECD=0.009 $\mu g\ L^{-1}$) was used.

Daily Flux was calculated using the method detailed by Parkin and Venterea (2010). The concentration of N_2O (ppmv) was plotted with respect to time (0, 15, 30, 45 min) and the slope was calculated to determine the N_2O flux in μL N_2O L^{-1} min^{-1}. The flux (μL N_2O L^{-1} min^{-1}) was transformed to μL N_2O m^{-2} day^{-1} by dividing the chamber volume (L), by the chamber surface area (m^2), and multiplying by the number of minutes in a day. The ideal gas law, PV=nRT, was used to convert μL N_2O m^{-2} day^{-1} into g N_2O-N ha^{-1} day^{-1}. A pressure of 0.9644 atm was used in the daily flux equation, which was derived from Table 1 in Parkin and Venterea (2010). This process is described algebraically in Equation 2.1.

$$\text{Daily Flux (g N}_2\text{O-N)} = \frac{\mu\text{L N}_2\text{O}}{\text{L} * \text{min}} * \frac{1440\text{ min}}{\text{day}} * \frac{1\text{ L N}_2\text{O}}{10^6\ \mu\text{L N}_2\text{O}} * \frac{11.6745\text{ L}}{0.0729659\text{ m}^2} * \frac{\text{K} * \text{mol}}{0.0821\text{ L} * \text{atm}} * \frac{\text{Pressure (atm)}}{\text{Temperature (K)}} * \frac{44.013\text{ g N}_2\text{O}}{1\text{ mol N}_2\text{O}} * \frac{28.0134\text{ g N}}{44.013\text{ g N}_2\text{O}} * \frac{10000\text{ m}^2}{\text{ha}}$$

Equation 2.1 Daily flux calculation.

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$$\text{Surface area} = \pi * 15.24\text{ cm} * 15.24\text{ cm} = 729.66\text{ cm}^2 = 0.072966\text{ m}^2$$

Equation 2.2 Sampling zone surface area.

$$\text{Volume} = 729.66\text{ cm}^2 * 16\text{ cm} = 11{,}674.54\text{ cm}^3 = 11.67454\text{ L}$$

Equation 2.3 Sampling chamber volume.

Cumulative area-scaled N_2O emissions were calculated using trapezoidal integration of daily fluxes vs time as described by Venterea et al. (2011):

$$\text{Cumulative flux (kg N}_2\text{O-N ha}^{-1}) = \sum_{i=1}^{n}\left[\frac{X_i + X_{i+1}}{2}\right] * (T_{i+1} - T_i)$$

Equation 2.4 Cumulative flux calculation. X_i is daily flux at initial time, X_{i+1} is daily flux at final time, T_i is time of initial flux, and T_{i+1} is time of final flux.

Yield-scaled nitrous oxide emissions, fertilizer induced emissions, and emissions factor were calculated using the following formulas:

$$\text{Yield- scaled nitrous oxide emissions } (\text{g } \mathrm{N_2O}\text{- N Mg}^{-1}\text{grain}) = \frac{\text{Cumulative flux } (\text{g } \mathrm{N_2O}\text{- N ha}^{-1})}{\text{Yield } (\text{Mg grain ha}^{-1})}$$

Equation 2.5 Yield-scaled nitrous oxide emissions (YSNE) calculation.

$$\text{Fertilizer induced emissions } (\text{kg } \mathrm{N_2O}\text{- N ha}^{-1}) = \text{Cumulative flux treatment X } (\text{kg } \mathrm{N_2O}\text{- N ha}^{-1}) - \text{Cumulative flux Check } (\text{kg } \mathrm{N_2O}\text{- N ha}^{-1})$$

Equation 2.6 Fertilizer induced emissions (FIE) calculation.

$$\text{Emissions factor } (\%) = \frac{\text{Fertilizer induced emissions } (\text{kg } \mathrm{N_2O}\text{- N ha}^{-1})}{\text{Fertilizer applied } (\text{kg } \mathrm{N_2O}\text{- N ha}^{-1})} * 100$$

Equation 2.7 Emissions factor (EF) calculation.

Statistics

Data were analyzed by site year as complete randomized block designs. Inter-site comparisons were not made due to treatment being a random effect across sites, but a fixed effect within sites. SAS v. 9.4 (SAS, Cary, NC) was the software used for all analyses. PROC MIXED was used to produce the ANOVA with treatments as the fixed effect and block treated as a random effect. Response variables assessed were cumulative flux, yield, yield-scaled nitrous oxide emissions, fertilizer induced emissions, and emissions factor. Additionally, Fisher’s Least Significant Difference (LSD) was used to make pairwise comparisons for all treatments and response variables. An alpha level 0.05 was used for all statistical analyses.

Results

Weather

During the growing season (May – September), Manhattan received 663 and 379 mm of precipitation in 2016 and 2017, respectively (Table 2.3). Prior to the growing season (January – April) Manhattan received 250 and 270 mm of precipitation in 2016 and 2017, respectively (Table 2.3). The most recent 30-year normal (1980 – 2010) for precipitation at Manhattan, KS was 171 mm and 534 mm of precipitation for the period of January – April, and May – September respectively (Table 2.3). Growing season precipitation was 24.2 percent above and 29.0 percent below normal precipitation for 2016 and 2017, respectively. Precipitation ahead of the growing season was 46.1 and 57.9 percent above normal in 2016 and 2017, respectively. Precipitation at Topeka during the 2017 growing season totaled 521 mm, which is 7.0 percent below normal precipitation of 560 mm (Table 2.3). Precipitation ahead of the growing season was 264 mm, which is 26.9 percent above the normal of 208 mm (Table 2.3). Additionally, Topeka received 256 mm of water via irrigation during the growing season (Table 2.4).

Grain Yield

Manhattan yield in 2016 ranged from 6.2 Mg ha^{-1} in the check to 11.3 Mg ha^{-1} in the Sensor treatment (Fig 2.1a and Table 2.5). Treatments receiving N yielded an average of 10.2 Mg ha^{-1}. Grain yield was not significantly different for the four N management systems; however, the N treatments yielded 64.1 percent higher than the check. In 2017, there were significant differences between the N treatments at Manhattan. All N treatments yielded higher than the Check. Average yield across all N treatments was 5.6 Mg ha^{-1}, or 194.7 percent higher than the Check (1.9 Mg ha^{-1}) (Fig 2.1b and Table 2.5). There was a significant difference between Sensor (4.4 Mg ha^{-1}) and Split-soil Test (6.7 Mg ha^{-1}), however no additional differences were observed between the four N management systems. Notably, Manhattan 2016 average yield (9.4 Mg ha^{-1}) across all treatments was 91.8 percent higher than Manhattan 2017 average yield (4.9 Mg ha^{-1}). Topeka was an irrigated site with a higher yield potential. Treatment yields ranging from 8.0 (Check) to 15.2 (Split-Soil Test) Mg ha^{-1} (Fig 2.1c and Table 2.5). Soil Test (14.1 Mg ha^{-1}) and Split-Soil Test (15.1 Mg ha^{-1}) yielded the highest (Table 2.4). The Sensor (10.2 Mg ha^{-1}) and Aerial NDVI (9.8 Mg ha^{-1}) were significantly lower than Soil Test and Split-Soil Test, but were significantly higher than the Check (8.0 Mg ha^{-1}). The average yield of all N treatments was 12.3 Mg ha^{-1} or 43.8 percent higher than the Check. Soil Test and Split-Soil Test averaged 14.7 Mg ha^{-1}, which is 83.8 percent higher than Check. Sensor and Aerial NDVI averaged 10.0 Mg ha^{-1}, which is 25 percent higher than Check.

Nitrous Oxide Emissions

Manhattan 2016 daily nitrous oxide emission averages ranged from 0.07 to 3.46 g N_2O-N day^{-1} ha^{-1} (Fig 2.2a). Two dates of elevated fluxes were observed. On the 2 June daily fluxes ranged between 0.51 (Check) and 1.77 (Soil Test) g N_2O-N ha^{-1} day^{-1}. Similarly, on 28 June daily fluxes ranged from 0.94 (Check) to 3.46 (Split-Soil Test) g N_2O-N ha^{-1} day^{-1}. In 2017 flux averages ranged from 0.04 to 7.02 g N_2O-N ha^{-1} day^{-1} (Fig 2.2b). Pronounced daily fluxes were observed on 24 May, which ranged from 1.22 (Sensor) and 7.02 (Split-Soil Test) g N_2O-N ha^{-1} day^{-1}. Topeka flux averages ranged from 0.03 – 9.48 g N_2O-N ha^{-1} day^{-1} (Fig 2.2c). An elevated flux period was observed 9 May through 24 July when fluxes ranged between 0.38 and 9.48 g N_2O-N ha^{-1} day^{-1}.

Cumulative N_2O emissions in 2016 at Manhattan ranged from 0.03 (Check) to 0.08 (Split-soil test) kg N_2O-N ha^{-1} (Fig 2.3a and Table 2.6); however, no significant differences were observed. In 2017 at Manhattan values ranged from 0.04 (Check, Soil Test, Sensor) to 0.10

(Split-Soil Test) kg N_2O-N ha^{-1} (Fig 2.3b and Table 2.6), but there were no significant differences among treatments. Likewise, Topeka showed no significant differences between treatments with values between 0.06 (Aerial NDVI) and 0.14 (Soil Test) kg N_2O-N ha^{-1} (Fig 2.3c and Table 2.6).

Yield-scaled Nitrous Oxide Emissions, Fertilizer Induced Emissions, and Emissions Factor

Yield-scaled nitrous oxide emissions was lowest at 3.9 (Sensor) and highest at 7.5 (Split-Soil Test) g N_2O-N Mg^{-1} grain, which averaged 5.6 g N_2O-N Mg^{-1} grain at Manhattan in 2016 (Fig 2.4a and Table 2.7). No significant differences were observed at Manhattan in 2016. However, in 2017 at Manhattan the Check (25.0 g N_2O-N Mg^{-1} grain) was significantly higher than the treatments receiving N which ranged from 6.7 (Soil Test) to 12.2 (Split-soil Test) g N_2O-N Mg^{-1} grain (Fig 2.4b and Table 2.7). Average YSNE at Manhattan in 2017 was 12.0 g N_2O-N Mg^{-1} grain. Average YSNE at Topeka in 2017 was 7.8 g N_2O-N Mg^{-1} grain. Values ranged from 5.7 (Split-soil Test) to 10.3 (Soil Test) g N_2O-N Mg^{-1} grain with no significant differences (Fig 2.4c and Table 2.7).

No differences across all site-years were observed for FIE (Table 2.8). Fertilizer induced emissions were between 0.02 (Sensor and Aerial NDVI) and 0.05 (Split-Soil Test) kg N_2O-N ha^{-1} at Manhattan in 2016 (Table 2.8). Average FIE across the four N management systems in 2016 was 0.03 kg N_2O-N ha^{-1}. In 2017, FIE averaged 0.01 kg N_2O-N ha^{-1} at Manhattan and values were between -0.01 (Soil Test and Sensor) and 0.06 (Split-Soil Test) kg N_2O-N ha^{-1} (Table 2.8). Topeka FIE averaged 0.02 kg N_2O-N ha^{-1} and ranged from -0.01 (Aerial NDVI) and 0.07 (Soil Test) kg N_2O-N ha^{-1} (Table 2.8). No significant differences were observed at any site-year for EF. (Table 2.9). Emissions factor ranged from 0.02 (Soil Test, Sensor, and Aerial NDVI) and

0.03 (Split-Soil Test) percent and averaged 0.2 percent at Manhattan in 2016. Similarly, Manhattan 2017 EF ranged between 0.00 (Soil Test, Sensor, Aerial NDVI) and 0.02 (Split-Soil Test) percent and averaged 0.01 percent. Topeka EF ranged between -0.01 (Aerial NDVI) and 0.03 (Soil Test) percent and averaged 0.01 percent.

Discussion

Grain Yield

Grain yields and yield response to N strategy varied between site years. Treatments excluding the Check averaged 10.2 Mg ha^{-1} at Manhattan in 2016 compared to the non-irrigated Northeast District dryland average of 9.4 Mg ha^{-1}(NASS, 2019), which is a difference of 8.5 percent. However, the Manhattan average yield was 12.8 percent lower than the 11.7 Mg ha^{-1} average of a Kansas State University dryland yield trial conducted during 2016 in Manhattan (K-State, 2019). In 2017, all treatments receiving N yielded higher than the Check at Manhattan. The average yield of treatments receiving N was 5.6 Mg ha^{-1}, which was 30.0 percent lower than the Northeast district average of 8.0 Mg ha^{-1}(NASS, 2019) and 66.1 percent lower than a Kansas State University dryland yield trial average (9.3 Mg ha^{-1}) conducted during 2017 in Manhattan (K-State, 2019). The 42.8 percent reduction in yield from 2016 to 2017 is largely attributable to a 284 mm decrease in precipitation during the growing season. Precipitation in the 2017 growing season was 29.0 percent below normal. Topeka corn yield average for treatments receiving N was 12.3 Mg ha^{-1}, which was 12.8 percent higher than the East Central district average of 10.9 Mg ha^{-1} (NASS, 2019) and 17.4 percent lower than a Kansas State University yield trial average (14.9 Mg ha^{-1}) conducted in Topeka (K-State, 2019). All N treatments yielded significantly higher than Check, but Soil Test and Split-Soil Test yielded significantly higher than all other N treatments.

The application of N significantly increase yields for all site-years compared to the check; however, not all N treatments performed the same for each site-year. Soil Test and Split-Soil Test were the highest N rates for all site years (Table 2.2). In 2016, all yield differences were not significant, whereas in 2017 Sensor was significantly lower than Split-Soil Test (Table 2.5). The Sensor underestimated N compared to the Split-Soil Test in 2017 (Tables 2.2 and 2.5). The Sensor rate was 60.4 percent lower than the Split-Soil Test rate. Barker and Sawyer (2010) found that sensors might have trouble differentiating between slight deficiency and adequacy. However, the difference between Soil Test and Sensor was not significant. Soil Test and Split-Soil Test were 142 kg N ha^{-1} higher than Sensor. Precipitation from January – April was 58.5 percent above normal. In the Split-Soil Test treatment, 33.2 percent of N was applied at planting, whereas 60.2 percent of N was applied at planting for Sensor. The higher percentage of N applied at planting, lower N rate, and wetter than normal conditions at planting have led to a lower yield. Soil Test recommendations may overestimate the agronomic optimum N rate (AONR) for rainfed environments based on 2016 and 2017 results at Manhattan (Table 2.4). Sensor approaches may offer opportunity to maintain yield, reduce applied N, and lower input costs in rainfed environments (Roberts et al., 2010; Thompson et al., 2015). Conversely, Soil Test and Split-Soil Test yielded the highest at Topeka when other strategies underestimated the appropriate N rate (Tables 2.2 and 2.5). The other N treatments yielded higher than the check, but failed to optimize yield likely due to lower N rates. The higher N rates recommended by soil tests may be appropriate in irrigated environments where moisture is not limited, lending itself to increased yields and higher leaching potential (Quemada et al., 2013). Perhaps the algorithms supporting the individual strategies need to be refined to account for the influences of rainfed and irrigated environments as algorithm performance hinges on similarity of growing conditions and conditions in which the algorithm was developed (Bean et al., 2018). Due to the stark differences between the growing seasons in 2016 and 2017 at Manhattan and a single site year of an irrigated environment at Topeka additional research is needed to fully assess the potential of the various strategies to optimize corn yield. Furthermore, developing an N response for individual site-years would allow for validation of the N management strategies and their potential to predict agronomic optimum N rate.

Nitrous Oxide Emissions

Manhattan 2016 daily nitrous oxide emission averages ranged from 0.07 to 3.46 g N_2O-N day^{-1} ha^{-1} (Fig 2.2a). Two dates of elevated fluxes were observed (2 June and 28 June) following rainfall events greater than 20 mm. Similarly, Fernández et al. (2015) reported that nitrous oxide fluxes were greatest following rain events greater than 20 mm. In 2017 flux averages ranged from 0.04 to 7.02 g N_2O-N ha^{-1} day^{-1} (Fig 2.2b). Elevated fluxes were observed on 24 May following a rainfall event greater than 20 mm. Topeka flux averages ranged from 0.03 to 9.48 g N_2O-N ha^{-1} day^{-1} (Fig 2.2). A prolonged elevated flux period not seen at Manhattan in 2016 or 2017 may stem the 256 mm of irrigation applied at Topeka. Maximum daily fluxes across all site-years were considerably lower than 113 g N_2O-N ha^{-1} day^{-1} from a broadcast urea in a no-till system on a Kennebec silt loam observed near Manhattan, KS by Bastos (2015). Peak emissions observed across all site-years (9.48 g N_2O-N ha^{-1} day^{-1}) were 92 percent lower than peak emissions observed by Bastos (2015). Low daily N_2O fluxes are reflected in low cumulative N_2O emissions, and partly explains the lack of significant difference in cumulative N_2O emissions.

Cumulative nitrous oxide emissions were not significantly different within any site-years. Lack of significant differences among treatments may stem from N_2O being overshadowed by other loss pathways such as leaching, which can manifest as a prominent loss pathway in irrigated systems (Quemada et al., 2013), which may partially explain low N_2O emissions at Topeka. Other studies have shown that N_2O increases exponentially with increasing N rate (Hoben et al., 2011; Shcherbak et al., 2014). The study design did not include a range of N rates so it is not possible to determine if emission were increasing exponentially. However, Hoben et al. (2011) reported an exponential increase with a peak N application rate of 225 kg N ha^{-1}, which was lower than peak N rates at Manhattan 2017 and Topeka. Additionally, some studies have found difference in cumulative N_2O from application timing. Burzaco et al. (2013) found that N_2O increased due to side-dress application. However, other studies have found that split application and side-dress are best management practices for reducing N_2O (Fernández et al., 2016; Eagle et al., 2017). Studies showing increased N_2O from side-dress or split applications have had considerable rainfall close to the time of application (Burzaco et al., 2013; Venterea and Coulter, 2015) and was likely attributable to WFPS exceeding 60 percent (Weier et al., 1993; Sehy et al., 2003). No differences in timing were observed in this experiment across all site-year despite the potential for higher moisture at the time of application at Manhattan in 2016 and Topeka in 2017. Lack of significant differences between the four N management systems suggests that N_2O production was not a prominent loss pathway. Additionally, N rates in this study may have been at or below the optimum N rate. Ma et al. (2010) and Eagle et al. (2017) found that surpassing agronomic optimum N rate led to disproportionate increase in N_2O. Low N_2O in this study maybe attributable to N rates remaining at or below the agronomic optimum, which may be magnified by low soil organic matter.

Values observed from all site-years ranged from 0.03 to 0.14 kg N_2O-N ha^{-1} (Table 2.6). Average cumulative nitrous oxide emissions were 0.05, 0.05, and 0.09 kg N_2O-N ha^{-1} for Manhattan 2016, Manhattan 2017, and Topeka 2017, respectively. which were lower than many reported values. A rainfed corn study conducted in Indiana reported values ranging from 0.81 to 3.52 kg N_2O-N ha^{-1} (Burzaco et al., 2013). The study by Burzaco et al. (2013) was conducted on a conventionally tilled Chalmers silty clay loam in 2010 and 2011 near West Lafayette, IN where the mean 30-year precipitation is 970 mm and temperature is 10.5˚C. Organic matter was 3.3 and 4.4 percent in 2010 and 2011, respectively. The maximum N rate applied was 180 kg N ha^{-1}. Another dryland corn study conducted in Illinois reported values ranging from 0.97 to 16.89 kg N_2O-N ha^{-1} (Fernández et al., 2015). The study by Fernandez et al. (2015) was conducted on a Flanagan silt loam and Drummer silty clay loam with organic matter ranging from 3.5 to 3.6 percent near Urbana, IL from 2009 to 2011. The 30-year average annual precipitation is 1044 mm and mean temperature is 11.2˚C. The maximum N rate applied was 180 kg N ha^{-1}. A rainfed corn study in Canada reported values ranging from 0.08 to 1.75 kg N_2O-N ha^{-1} (Ma et al., 2010). This study was conducted on-farm near Ottawa, ON; Guelph, ON; and Saint-Valentine, QC. Soil organic matter ranged from 1.2 to 2.6 percent, and the highest N rate was 150 kg N ha^{-1}. Another study near Manhattan, KS reported 0.3 to 3.5 kg N_2O-N ha^{-1} (Bastos, 2015). This study was conducted on a Kennebec silt loam and the N rate was 168 kg N ha^{-1}. Lastly, an irrigated corn study in Colorado reported values ranging from 0.1 to 1.7 kg N_2O-N ha^{-1} (Halvorson et al. 2011). The study was conducted near Fort Collins, CO on a strip-tilled Fort Collins clay loam. The 30-year average annual precipitation is 383 mm and the mean temperature is 8.9˚C. The soil organic matter was 1.2 percent and the N rate was 202 kg N ha^{-1}. Upper values from this experiment were toward the lower range of values reported in the literature.

Yield-scaled Nitrous Oxide Emissions, Fertilizer Induced Emissions, and Emissions Factor

Yield-scaled nitrous oxide emissions allows for the assessment of treatment effects on emissions and yield simultaneously. Differences in YSNE in 2016 were not significant despite significant differences in yield (Table 2.7). The Check was the lowest in yield and cumulative emissions. By having the lowest yield and lowest cumulative emissions the Check had a similar YSNE compared to the N treatments. Conversely, in 2017 the Manhattan Check had a significantly higher YSNE than the N treatments (Table 2.7). Cumulative emissions were similar across all treatments; however, yield was significantly lower for the Check. Similar cumulative emissions and substantially lower yield resulted in the Check having the highest YSNE. Despite differences in yield among treatments at Topeka no differences were observed in YSNE (Table 2.7). Lack of significant differences may be attributable to variability among replications. Data from Manhattan 2016 and Topeka 2017 suggest that N strategy was not a significant influence on YSNE; however, Manhattan 2017 data indicates that YSNE may increase due to no fertilization because of a precipitous decrease in yield. While over application of N has been documented to increase YSNE, forgoing N may have similar effects (Kim and Giltrap, 2017). Observed values ranged from 3.9 to 25.0 g N_2O-N Mg^{-1} grain (Table 2.7). Average YSNE was 9.4, 4.9, and 11.5 g N_2O-N Mg^{-1} grain for Manhattan 2016, Manhattan 2017, and Topeka 2017, respectively. Values were considerably lower than values reported by Burzaco (2013), which ranged from 135 to 418 g N_2O-N Mg^{-1} grain (see previous section for site description). Similarly, An irrigated corn study in Colorado reported YSNE values ranging from 15 to 121 g N_2O-N Mg^{-1} grain (Halvorson et al., 2011) (see previous section for site description). Low YSNE likely corresponds to lower cumulative emissions discussed in the previous section.

No differences were observed among treatments for FIE (Table 2.8). Fertilizer induced emissions ranged between -0.01 and 0.07 kg N_2O-N ha^{-1}. Average FIE was 0.03, 0.01, 0.02 kg N_2O-N ha^{-1} for Manhattan 2016, Manhattan 2017, and Topeka 2017, respectively. Likewise, no significant differences were observed for EF (Table 2.9). Emissions factor ranged between -0.01 to 0.03 percent. Average EF was 0.02, 0.01, and 0.01 percent for Manhattan 2016, Manhattan 2017, and Topeka 2017. The EF observed for all sites is in stark contrast with the IPCC EF of 1 percent (Klein, et al., 2006). Other studies have found that the IPCC EF is a poor approximation and does not reflect the dynamic nature and variability associated with N_2O from cropping systems (Kim et al., 2013; Shcherbak et al., 2014). In two Colorado irrigated corn studies Halvorson et al. reported EF >0.3 percent (2010) and >0.8 percent (2011). The study by Halvorson et al. (2011) was described in the previous section, and the site conditions for Halvorson et al. (2010) were similar Halvorson et al. (2011) except that the site was no tilled. An on-farm rainfed corn study in Canada reported EF values ranging from 0.1 to 1.45 percent (Ma et al., 2010) (see previous section for site description). Additionally, a rainfed corn study conducted in Illinois reported EF values ranging from 0.00 to 8.15 percent (Fernández et al., 2015) (see previous section for site description). Bastos (2015) reported EF values ranging from 0.4 to 1.3 percent (see previous section for site description). Observed values and values reported in the literature suggest that the IPCC EF overestimates many systems and reflects only the most intensively managed systems (Kim et al., 2013).

Conclusions

The performance of N management strategies varied between site-years and metric of interest. There were no significant difference in N management strategies with respect to yield in 2016; however, Split-Soil Test yielded significantly higher than Sensor. Soil Test and Split-Soil

Test yielded significantly higher than Sensor and Aerial NDVI at Topeka in 2017. Differences in site-characteristics and weather between site years suggest that one N management strategy may not be appropriate for all growing environments. The calibrations and algorithms that underpin conventional and sensor-based recommendations should be tailored to the growing environment and yield potential. No significant difference in cumulative N_2O emissions occurred at any of the site-years. This suggests that N_2O emissions may not be a prominent N loss pathway for the sites studied in this research. Cumulative emissions ranged from 0.03 – 0.14 kg N ha^{-1}, which was toward the lower end of values reported in the literature. YSNE was not significantly different among the five treatments at Manhattan 2016 and Topeka. However, YSNE was significantly higher in the Check at Manhattan 2017. This may be attributable to dry conditions in 2017 that led to steep yield losses, particularly in the Check. The emission factor was not significantly different at any of the site years and values ranged from -0.01 to 0.03 percent on continuously tilled, low organic matter, river bottom silt loam soils with surface applied N fertilizer at agronomic N rates, which is markedly lower than the IPCC default value of one percent. Further research is needed across a breadth of growing environments to assess the potential of N management strategies to positively affect yield and N_2O emissions, because it appears from this experiment that a one-size-fits-all approach may not be suitable.

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Table 2.1 Early-season soil test values reported from the Kansas State University Soil Test Laboratory. Sampling depth was 0 – 15 cm for all parameter except for nitrate, which was 0 – 61 cm.

	Manhattan		**Topeka**
	2016	2017	2017
NO_3-N (ppm)	5.5	4.0	7.4
NH_4-N (ppm)	14.3	11.9	20.0
P (ppm)	61.4	46.0	64.4
K (ppm)	214	193	440
pH	5.6	5.7	6.8
Buffer pH	6.9	6.8	9.0
Organic Matter (%)	1.6	1.6	2.5

Table 2.2 Nitrogen application rates and timings for all site-years.

	Manhattan						**Topeka**		
	2016			2017			2017		
Treatment	Date(s)	Growth Stage(s)	Rate(s) kg N ha^{-1}	Date(s)	Growth Stage(s)	Rate(s) kg N ha^{-1}	Date(s)	Growth Stage(s)	Rate(s) kg N ha^{-1}
Check	-	-	-	-	-	-	-	-	-
Soil Test	22 April	Planting	185	21 April	Planting	235	24 April	Planting	258
Split-Soil Test	22 April	Planting	62	21 April	Planting	78	24 April	Planting	84
	20 May	V6-8	123	6 July	V8	157	7 July	V8	174
Sensor	22 April	Planting	56	21 April	Planting	56	24 April	Planting	56
	9 June	V10-12	22	6 July	V8	37	7 July	V8	39
Aerial NDVI	22 April	Planting	56	21 April	Planting	56	24 April	Planting	56
	9 June	V10-12	63	6 July	V8	112	7 July	V8	112

Table 2.3 Monthly precipitation for all site-years.

Month	**Manhattan** 2016	**Manhattan** 2017	**Manhattan** Normal	**Topeka** 2017	**Topeka** Normal
	---mm---				
January	13	25	17	29	22
February	11	11	27	8	33
March	11	107	56	95	63
April	215	127	71	132	90
May	177	97	114	140	125
June	39	72	129	138	137
July	155	34	101	65	97
August	186	155	109	147	108
September	106	21	81	31	93
October	70	93	56	86	77
November	8	2	41	2	47
December	21	3	26	7	34
Total	1012	747	828	880	926

Table 2.4 Irrigation schedule Topeka 2017.

Date	**Amount Applied**
	---------mm---------
16 June	29
22 June	27
5 July	34
12 July	28
15 July	26
20 July	29
25 July	27
10 August	28
15 August	28
Total	256

Table 2.5 Grain yield for all site-years.

Treatment	**Manhattan** 2016	 2017	**Topeka** 2017
	------------------------------Mg grain ha^{-1}		------------------------------
Check	6.2b§	1.9c	8.0c
Soil Test	9.3a	5.7ab	14.1a
Split-Soil Test	10.3a	6.7a	15.2a
Sensor	11.3a	4.4b	10.2b
Aerial NDVI	9.8a	5.7ab	9.8b
Pr>F	*0.012*	*<0.001*	*<0.001*
lsd$_{0.05}$	*2.6*	*1.7*	*1.5*

§ Treatment means within a site-year followed by different letters are significantly different (α=0.05).

Table 2.6 Cumulative nitrous oxide emissions for all site-years.

Treatment	Manhattan 2016	Manhattan 2017	Topeka 2017
	-------------------------------kg N_2O-N ha^{-1}		-------------------------------
Check	0.03	0.04	0.07
Soil Test	0.06	0.04	0.14
Split-Soil Test	0.08	0.10	0.09
Sensor	0.05	0.04	0.07
Aerial NDVI	0.05	0.05	0.06
Pr>F	*0.221*	*0.413*	*0.673*
$lsd_{0.05}$	-	-	-

Table 2.7 Yield-scaled nitrous oxide emissions (YSNE) for all site-years.

Treatment	**Manhattan** 2016	**Manhattan** 2017	**Topeka** 2017
	--------------------------g N_2O-N Mg^{-1} grain		--------------------------
Check	4.7	25.0a§	9.4
Soil Test	6.8	6.7b	10.3
Split-Soil Test	7.5	12.2b	5.7
Sensor	3.9	8.3b	7.1
Aerial NDVI	5.0	7.9b	6.6
Pr>F	*0.356*	*0.006*	*0.858*
$lsd_{0.05}$	-	*8.3*	-

§ Treatment means within a site-year followed by different letters are significantly different (α=0.05).

Table 2.8 Fertilizer induced emissions (FIE) for all site-years.

Treatment	**Manhattan** 2016	**Manhattan** 2017	**Topeka** 2017
	------kg N_2O-N ha^{-1}------		
Soil Test	0.03	-0.01	0.07
Split-Soil Test	0.05	0.06	0.01
Sensor	0.02	-0.01	0.00
Aerial NDVI	0.02	0.00	-0.01
Pr>F	*0.477*	*0.337*	*0.617*
$lsd_{0.05}$	-	-	-

Table 2.9 Emissions factor (EF) for all site-years.

Treatment	**Manhattan** 2016	 2017	**Topeka** 2017
	-------------------------% N_2O-N N^{-1} applied-------------------------		
Soil Test	0.02	0.00	0.03
Split-Soil Test	0.03	0.02	0.01
Sensor	0.02	0.00	0.00
Aerial NDVI	0.02	0.00	-0.01
Pr>F	*0.921*	*0.299*	*0.664*
$lsd_{0.05}$	-	-	-

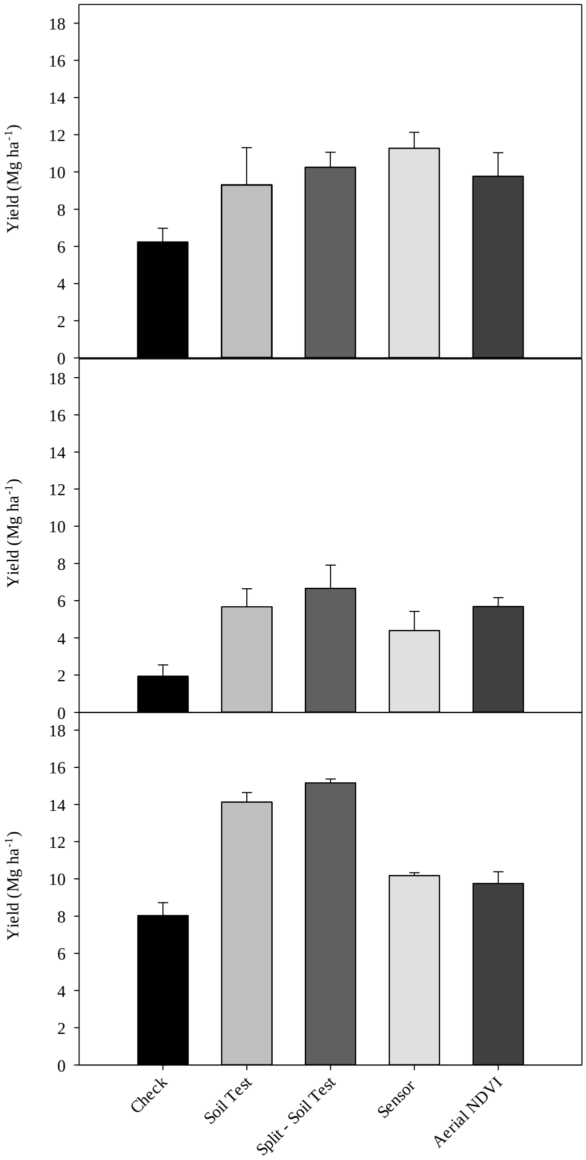

Figure 2.1 Grain yield for Manhattan 2016 (a), Manhattan (b), and Topeka (c). Vertical bars represent standard error.

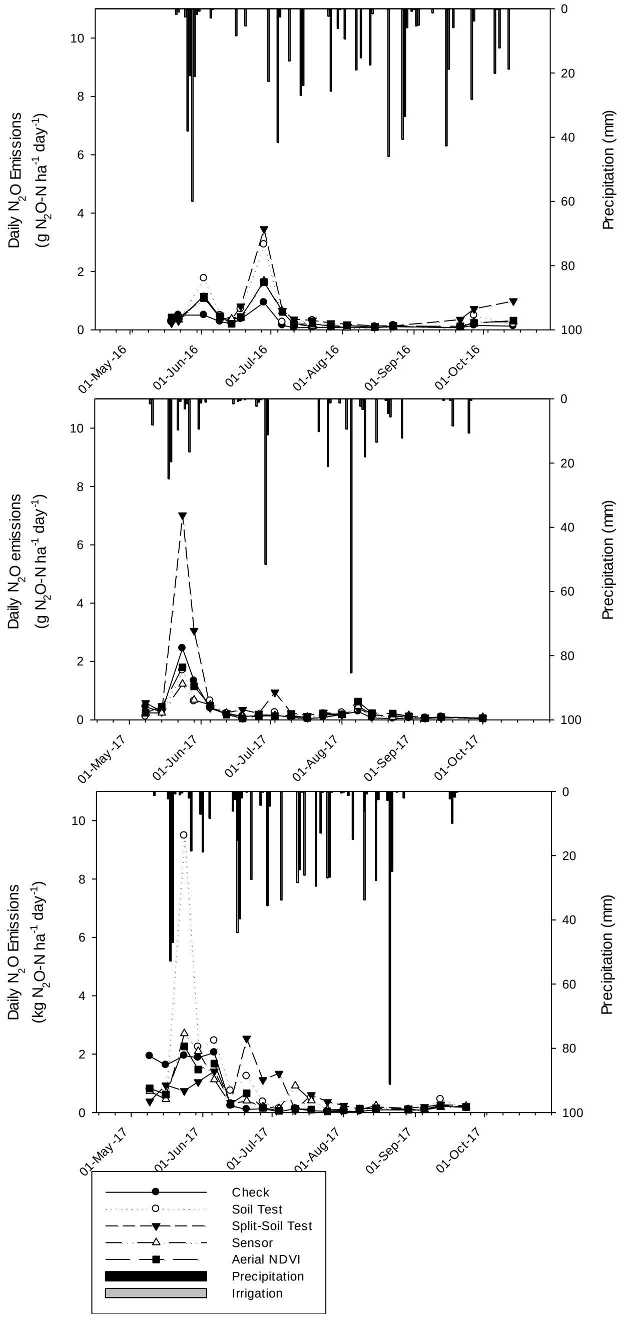

Figure 2.2 Daily nitrous oxide (N_2O) fluxes, precipitation, and irrigation (Topeka only) for Manhattan 2016 (a), Manhattan 2017 (b), and Topeka 2017 (c).

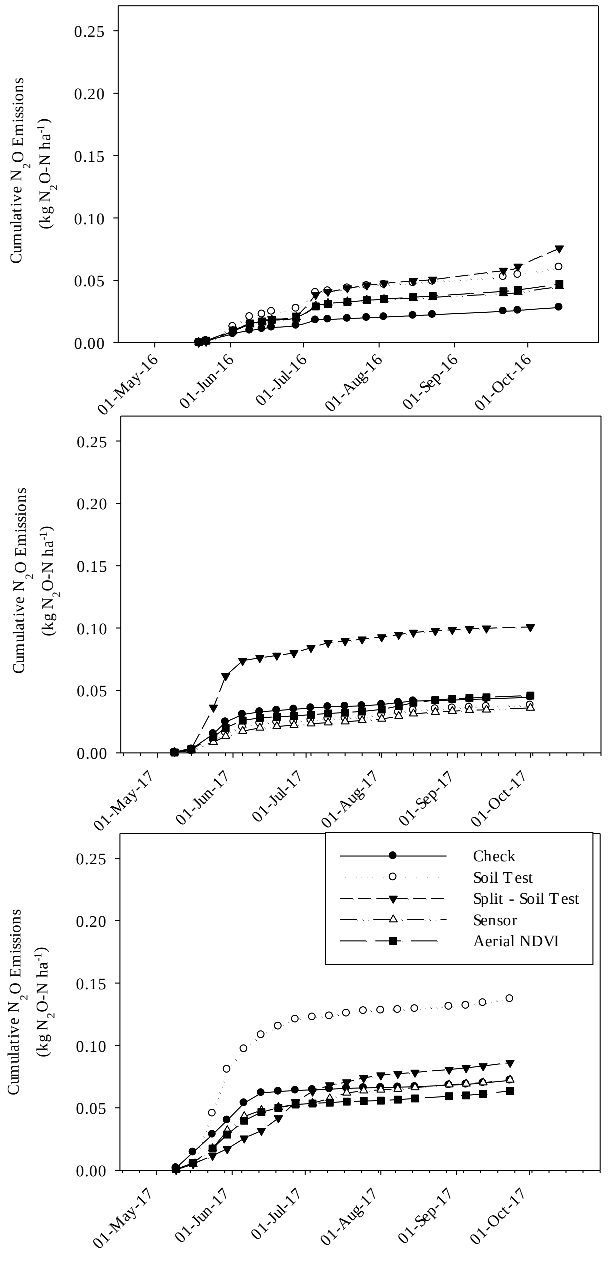

Figure 2.3 Cumulative nitrous oxide emissions for Manhattan 2016 (a), Manhattan 2017 (b), and Topeka 2017 (c).

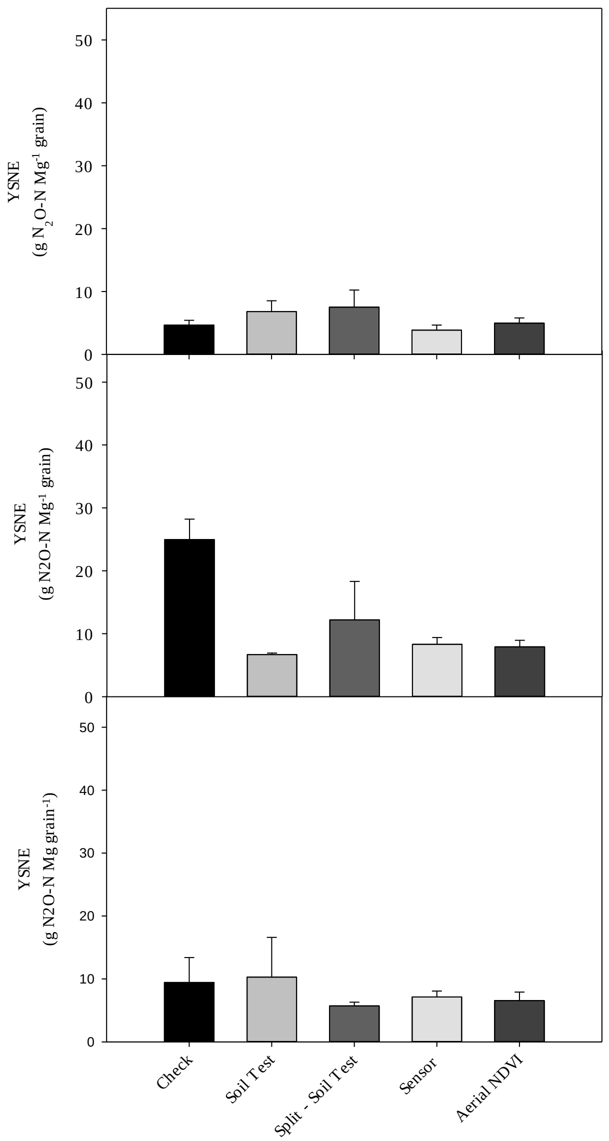

Figure 2.4 Yield-scaled nitrous oxide emissions (YSNE) for Manhattan 2016 (a), Manhattan 2017 (b), and Topeka 2017 (c). Vertical bars represent standard error.

Appendix A - Soil Moisture Calibration

Assessing the Need For Laboratory-based Calibration of the FieldScout TDR-300

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Abstract

There is a growing interest among producers and consultants to quickly determine soil moisture for in-season management decisions. An array of portable soil moisture probes have entered the market. Pre-packaged algorithms are used to calculate soil moisture content; however, these algorithms may not represent the soil of interest. A laboratory-based calibration allows a soil moisture calibration curve to be developed for a specific soil and instrument. A Belvue silt loam soil and a Eudora silt loam soil were collected from the field and passed through a 2-mm to remove soil structure. Bulk densities for the respective fields were calculated at 1.32 g cm^{-3}. Prior to soil compaction the soil was brought to 1 of 5 predetermined approximate volumetric water contents (VWC) by adding 0.005 M $CaSO_4$. Soil was compacted in a polyvinyl chloride (PVC) ring with a 7.6-cm internal diameter and height of 15.8-cm to a bulk density of 1.32 g cm^{-3}. Five, 3-cm layers of soil were compacted one at a time. The FieldScout TDR 300 equipped with 7.6 cm tines was inserted into the soil core and the measured VWC was recorded. A subsample was collected and oven dried to determine actual VWC. Measured VWC (MVWC) was regressed against actual VWC (AVWC) in Excel 2016. Measured VWC and actual VWC were strongly correlated for Belvue (r^2= 0.9969) and Eudora (r^2=0.9897).Root mean square error (RMSE) for Belvue and Eudora were respectively 0.0097 and 0.0183. Minimal RSME values suggest that probe was precise; however, accuracy did not match the findings of precision. The regression equation for Belvue was MVWC= 1.0092*AVWC – 0.0159 and MVWC=

1.2494*AVWC – 0.0320 for Eudora. Belvue provided a reasonable estimate of VWC, but the MVWC for Eudora varied considerable from the AVWC. The inaccuracy of the probe for the Eudora soil illustrates the need to calibrate for the soil of interest.

Introduction

There is a growing interest among producers and consultants to quickly determine soil moisture for in-season management decisions. TDR technologies measure the dielectric permittivity of the soil to determine soil water content. Dielectric permittivity is a property of the soil that will influence the amount of time for an electrical pulse to travel between TDR tines, or the anode and cathode. Dielectric permittivity is unique to each soil, and factors such as soil mineralogy, temperature, electrical conductivity are factors that influence dielectric permittivity (Jones et al., 2002; Robinson et al., 2002). Consequently, it is important to calibrate TDR devices for soil type in order to obtain accurate results. Pre-packaged algorithms may not represent the soil of interest, which may yield misleading values. The Spectrum Technologies, Inc. FieldScout TDR 300 equipped with 3-inch (7.6-cm) tines was used to conduct an ex-situ calibration on a Belvue silt loam and a Eudora silt loam. The FieldScout TDR 300 provides users with percent volumetric water content (%VWC). Percent volumetric water content can be converted to a more common decimal form, which will be referred to as VWC via the formula below:

$$\mathrm{VWC} = \frac{\%\mathrm{VWC}}{100}$$

Equation A.1 Relationship between volumetric water content (VWC) and percent volumetric water content (%VWC)

%VWC is the percent of water occupying the total soil volume. This should not be confused with gravimetric water content (GWC), which is the amount of water in soil on a mass basis. Likewise, percent saturation or water filled pore space should not be mistaken for VWC, because percent saturation and water filled pore space represent the percent of soil pore volume occupied by water. The objective was to assess the accuracy and precision of the TDR 300 across a range of soil moisture contents for two different soils. It was hypothesized that the calibration curve would vary between the Belvue silt loam and Eudora silt loam.

Methods

Bulk density samples were collected from Ashland Bottoms Research Farm and Kansas River Valley Experiment Field, respectively consisting of a Belvue silt loam and Eudora silt loam. 3 in. (7.5 cm) long bulk density rings with an internal diameter of 2.87 in. (7.3 cm) were used to collect bulk density cores. Four cores for each soil were extracted and placed in a convection oven at 221 ˚F (105 ˚C) until the soil mass was constant. Bulk density was calculated using the formula below:

$$\text{bulk density (g soil cm}^{-3}\text{ soil)} = \frac{\text{oven dry soil mass (g)}}{\text{volume of ring (cm}^{3}\text{)}}$$

Equation A.2 Bulk density equation.

The Belvue silt loam and Eudora silt loam both had the same bulk density of 1.32 g cm^{-3}.

Four five-gallon buckets of soil were collected from the top 3 in. (7.6 cm) of each soil. Soil was passed through a number 10 sieve (2 mm) to ensure soil size uniformity. Soil was dried in the laboratory for one week at approximately 65 ˚F (18.3 ˚C) and turned daily to ensure uniform drying. After drying was complete, six two-gallon plastic bags, three for each location, were filled with soil and a sub-sample of 1.76 oz. (50 g) of soil was placed in the convection oven at 221 ˚F (105 ˚C) and the final mass of soil was recorded. Gravimetric water content (GWC) was determined using the formula below:

$$G\text{WC (g H}_2\text{0 g}^{-1}\text{soil)} = \frac{\text{intitial soil mass (g)} - \text{oven dry soil mass (g)}}{\text{oven dry soil mass (g)}}$$

Equation A.3 Gravimetric water content (GWC) equation.

GWC is essential to compacting soil to the proper bulk density, because water mass must be accounted for.

Soil was compacted in a polyvinyl chloride (PVC) ring with a 3 in. (7.6-cm) internal diameter and height of 6.22 in. (15.8-cm). Five, 1.18 in. (3-cm) layers of soil were compacted one at a time and the weight of soil necessary for each layer was calculated using the following formulas:

$$\text{layer volume }(\text{cm}^3) = \pi \bullet \text{layer height (cm)} \bullet \text{ring radius (cm)} \bullet \text{ring radius (cm)}$$

Equation A.4 Layer volume equation.

$$\text{layer weight (g)} = \text{bulk density }(\text{g cm}^{-3}) * \text{layer volume }(\text{cm}^3) * (1 + \text{GWC})$$

Equation A.5 Layer weight equation.

Soil was then compacted using a wooden plunger that matched the internal dimensions of the PVC ring. The TDR 300 was calibrated prior to each measurement following manufacturer's guidelines. Standard VWC and high-clay VWC were used for the Belvue and Eudora soils, respectively. Upon taking a measurement, a 3 in. (7.6 cm) deep core was obtained from the center of the PVC ring to determine GWC by oven drying the soil as described above. The GWC obtained was then then converted to determine actual VWC:

$$\text{actual VWC }(\text{g H}_2\text{O g soil}^{-1}) = \frac{\text{GWC} * \text{bulk density }(\text{g cm}^{-3})}{1\text{ g H}_2\text{O cm}^{-3}\text{ H}_2\text{O}}$$

Equation A.6 Actual volumetric water content (AVWC) equation.

Three intermediate moisture contents and a saturated moisture content were prepared in addition to the initial air-dry moisture content. The intermediate moisture contents were prepared by raising the volumetric water content (VWC) by 0.07 cm^3/cm^3 for Belvue and 0.10 cm^3/cm^3 for Eudora. Soil with a known moisture content was partitioned to the equivalent of 141.10 oz (4000 g) of oven dry soil and was spread across a tarp to be wetted. Wetting was conducted using a solution of 0.005 M calcium sulfate solution to prevent soil dispersion. The dilute calcium sulfate solution was used to mimic the solute concentration of rain water and to prevent soil dispersion. The following formulas were used to calculate the necessary amount of calcium sulfate solution to be added to the soil:

$$\text{target GWC (g H}_2\text{O g soil}^{-1}) = \frac{\text{target VWC (cm}^3\text{ cm}^{-3}) * 1\text{ g cm}^{-3}\text{ H}_2\text{O}}{\text{bulk density (g cm}^{-3})}$$

Equation A.7 Target gravimetric water content (target GWC) equation.

$$\begin{aligned}&\text{solution mass (g)}\\&\qquad = 5 * (\text{target GWC} - \text{current GWC}) * \text{layer volume (cm}^3)\\&\qquad * \text{bulk density (g cm}^{-3})\end{aligned}$$

Equation A.8 Solution mass equation.

The desired mass of solution was delivered to the soil via a light mist from the spray bottle and soil mixed at regular intervals throughout the process to homogenize soil moisture.

Saturated soil conditions were simulated by immersing the soil cores in calcium sulfate solution. Soil rings were outfitted with cheese-clothe and four layers of fine fiberglass mesh (Saint-Gobain Adfors, Grand Island, NY) to retain the soil, but still allow calcium sulfate solution to pass through. Calcium sulfate solution was added into a 5-gallon plastic bucket containing the cores in 1.2 in. (3 cm) increments with a minimum of one hour between increments until there was 5.9 in. (15 cm) of standing solution in the bucket. TDR readings were taken with rings immersed in solution. The following equation was used to determine saturated water content:

$$\text{saturated VWC} = 1 - \frac{\text{bulk density (g cm}^{-3})}{2.65\text{ g cm}^{-3}}$$

Equation A.9 Saturated volumetric water content (saturated VWC) equation.

Actual VWC was regressed against measured VWC using Excel 2016 (Microsoft, Redmond, WA).

Results

Two criteria were explored when assessing the performance of the FieldScout TDR 300-precision and accuracy. Root mean square error represents the precision of the instrument. Accuracy, represents how close the probe reading is to actual VWC.

A strong linear correlation (r^2=0.9969) and a root mean square error (RMSE) of 0.0097 was observed for the Belvue silt loam. The fitted equation for the soil was:

$$\text{measured VWC} = 1.0092 * \text{actual VWC} + 0.0159$$

In Figure A.1a the regression line for the Belvue silt loam parallels the 1:1 line and is slightly offset, which suggests the probe provides a reasonable estimate of VWC for the Belvue silt loam. The FieldScout TDR 300 was both precise and accurate for the Belvue silt loam in standard VWC mode.

A strong linear correlation (r^2=0.9897) was also observed for the Eudora silt loam with an RMSE of 0.0183. The fitted equation follows:

$$\text{measured VWC} = 1.2494 * \text{actual VWC} - 0.032$$

While the instrument was precise, it was inaccurate. In Figure A.1b the regression line for the Eudora silt loam deviates appreciably from the 1:1 line. The deviation from the 1:1 line suggests that the probe may not provide a reasonable estimate as it overestimated VWC for the majority of observations. Data quality for both soils may have been influenced by the calculation of actual VWC. It was assumed for the saturated VWC measurement that all pore space was fully occupied by water; however, there was entrapped air that cannot be experimentally accounted for.

The probe displayed good precision in quantifying VWC; however, accuracy varied across the two soils. Measurements taken in the Belvue silt loam were accurate; whereas, accuracy was compromised in the Eudora silt loam. The disparity in accuracy illustrates the importance of calibrating a TDR probe to each soil. Results from this study show that the calibration curve for a TDR device is unique to a specific soil, and failing to calibrate may provide inaccurate data. Inaccurate soil moisture data may lend itself to adverse crop management decisions.

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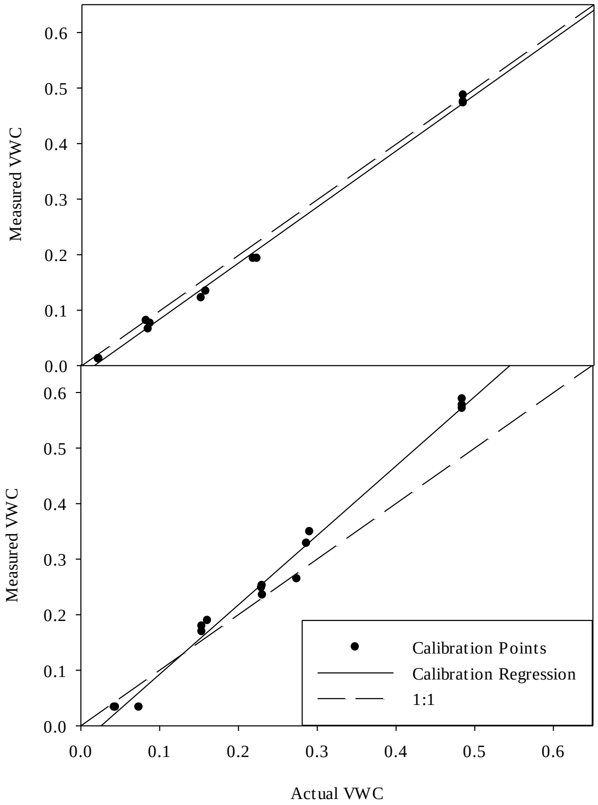

Figure A.1 Belvue silt loam (a) and Eudora silt loam (b) calibration.

Appendix B - Nitrous Oxide Moisture

Materials and Methods

Volumetric water content (VWC) was measured using a FieldScout 300 TDR (Spectrum Technologies, Aurora, IL). Four readings were taken approximately 0.3 m from the gas sampling chamber at the time of sampling. Standard VWC was used at Manhattan and high-clay VWC was used at Topeka. The average of the four readings was used to represent plot moisture.

Manhattan 2016 Moisture

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/28/16	Check	1	30.6	23.8	25.2	28.2	27.0
6/28/16	Check	2	17.2	20.8	18.2	15.5	17.9
6/28/16	Check	3	16.2	14.2	15.4	17.2	15.8
6/28/16	Check	4	18.4	14.5	13.9	17.2	16.0
6/28/16	Soil Test	1	33.6	24.3	31.8	25.2	28.7
6/28/16	Soil Test	2	23.5	20.5	23.2	23.5	22.7
6/28/16	Soil Test	3	18.5	16.2	17.5	20.2	18.1
6/28/16	Soil Test	4	20.8	19.2	16.5	19.6	19.0
6/28/16	Split-Soil Test	1	32.1	37.5	28.7	33.6	33.0
6/28/16	Split-Soil Test	2	28.5	24.2	22.8	25.5	25.3
6/28/16	Split-Soil Test	3	17.9	17.2	16.5	19.8	17.9
6/28/16	Split-Soil Test	4	16.5	17.2	12.2	20.2	16.5
6/28/16	Sensor	1	26.2	24.7	22.3	28.2	25.4
6/28/16	Sensor	2	16.2	17.9	18.5	16.9	17.4
6/28/16	Sensor	3	20.8	22.8	20.2	18.5	20.6
6/28/16	Sensor	4	17.9	14.2	14.9	17.2	16.1
6/28/16	Aerial NDVI	1	17.9	16.2	17.2	19.8	17.8
6/28/16	Aerial NDVI	2	18.5	18.2	19.5	20.2	19.1
6/28/16	Aerial NDVI	3	18.2	15.2	20.8	19.5	18.4
6/28/16	Aerial NDVI	4	18.2	18.9	12.6	20.2	17.5

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/11/16	Check	1	24.7	22.4	21.4	21.0	22.4
7/11/16	Check	2	17.9	17.9	14.9	13.0	15.9
7/11/16	Check	3	12.0	12.0	14.9	15.4	13.6
7/11/16	Check	4	18.4	13.9	13.5	16.4	15.6
7/11/16	Soil Test	1	18.4	17.8	17.2	17.1	17.6
7/11/16	Soil Test	2	20.3	17.9	13.5	19.3	17.8
7/11/16	Soil Test	3	14.9	11.5	16.9	18.4	15.4
7/11/16	Soil Test	4	20.3	13.5	12.5	16.4	15.7
7/11/16	Split-Soil Test	1	16.7	16.8	16.5	16.6	16.7
7/11/16	Split-Soil Test	2	25.7	22.3	18.4	26.7	23.3
7/11/16	Split-Soil Test	3	11.5	11.5	13.9	19.3	14.1
7/11/16	Split-Soil Test	4	12.5	13.5	9.0	8.1	10.8
7/11/16	Sensor	1	16.3	16.1	15.9	16.0	16.1
7/11/16	Sensor	2	14.4	15.4	12.0	13.9	13.9
7/11/16	Sensor	3	20.3	20.8	193.0	15.9	62.5
7/11/16	Sensor	4	10.5	14.4	12.5	16.4	13.5
7/11/16	Aerial NDVI	1	16.0	15.9	15.5	15.6	15.8
7/11/16	Aerial NDVI	2	16.4	17.9	17.9	18.4	17.7
7/11/16	Aerial NDVI	3	15.4	14.9	19.3	21.3	17.7
7/11/16	Aerial NDVI	4	17.9	15.9	12.5	14.4	15.2

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/19/16	Check	1	15.9	16.9	16.9	16.9	16.7
7/19/16	Check	2	19.9	20.8	21.3	20.3	20.6
7/19/16	Check	3	12.0	13.0	14.9	16.9	14.2
7/19/16	Check	4	12.5	13.9	16.4	13.9	14.2
7/19/16	Soil Test	1	8.5	15.4	16.5	9.5	12.5
7/19/16	Soil Test	2	23.8	20.3	23.9	24.3	23.1
7/19/16	Soil Test	3	12.0	13.9	15.9	18.4	15.1
7/19/16	Soil Test	4	15.4	12.5	15.4	14.4	14.4
7/19/16	Split-Soil Test	1	13.0	13.9	15.6	11.5	13.5
7/19/16	Split-Soil Test	2	24.3	21.8	21.8	24.3	23.1
7/19/16	Split-Soil Test	3	12.5	11.0	13.9	16.4	13.5
7/19/16	Split-Soil Test	4	0.9	9.5	11.0	10.0	7.9
7/19/16	Sensor	1	10.5	14.4	19.8	15.9	15.2
7/19/16	Sensor	2	17.4	16.4	18.4	14.9	16.8
7/19/16	Sensor	3	20.3	20.8	18.9	18.9	19.7
7/19/16	Sensor	4	12.5	15.4	14.4	18.4	15.2
7/19/16	Aerial NDVI	1	16.9	14.9	18.9	10.0	15.2
7/19/16	Aerial NDVI	2	16.9	21.8	20.8	20.3	20.0
7/19/16	Aerial NDVI	3	18.9	16.4	15.9	16.6	17.0
7/19/16	Aerial NDVI	4	13.0	14.4	12.5	16.4	14.1

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/27/16	Check	1	22.8	20.3	20.3	20.3	20.9
7/27/16	Check	2	15.9	18.9	19.8	20.8	18.9
7/27/16	Check	3	15.9	13.9	19.3	18.4	16.9
7/27/16	Check	4	15.9	14.9	15.4	19.3	16.4
7/27/16	Soil Test	1	15.9	14.9	16.4	20.3	16.9
7/27/16	Soil Test	2	24.3	20.8	20.3	22.8	22.1
7/27/16	Soil Test	3	14.9	14.9	19.3	16.9	16.5
7/27/16	Soil Test	4	20.3	16.4	15.9	20.3	18.2
7/27/16	Split-Soil Test	1	22.3	21.8	21.3	21.8	21.8
7/27/16	Split-Soil Test	2	25.7	21.8	26.2	24.7	24.6
7/27/16	Split-Soil Test	3	12.5	14.9	16.9	16.4	15.2
7/27/16	Split-Soil Test	4	14.4	13.0	9.0	13.5	12.5
7/27/16	Sensor	1	22.8	19.3	20.8	22.3	21.3
7/27/16	Sensor	2	14.4	16.9	18.9	18.4	17.2
7/27/16	Sensor	3	23.8	22.8	16.9	16.4	20.0
7/27/16	Sensor	4	18.9	18.9	13.5	15.4	16.7
7/27/16	Aerial NDVI	1	24.3	24.3	20.3	20.8	22.4
7/27/16	Aerial NDVI	2	18.4	17.4	15.9	20.8	18.1
7/27/16	Aerial NDVI	3	16.9	18.9	21.3	19.3	19.1
7/27/16	Aerial NDVI	4	16.4	16.4	18.9	20.8	18.1

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/15/16	Check	1	24.7	24.3	24.7	24.7	24.6
8/15/16	Check	2	23.3	24.7	22.4	23.3	23.4
8/15/16	Check	3	16.9	18.4	23.8	21.3	20.1
8/15/16	Check	4	21.8	19.8	20.8	22.8	21.3
8/15/16	Soil Test	1	21.3	19.3	17.4	22.8	20.2
8/15/16	Soil Test	2	24.7	26.2	24.7	25.7	25.3
8/15/16	Soil Test	3	17.4	18.4	21.3	19.3	19.1
8/15/16	Soil Test	4	20.8	20.3	16.9	21.8	20.0
8/15/16	Split-Soil Test	1	25.2	24.3	24.3	24.7	24.6
8/15/16	Split-Soil Test	2	28.2	26.2	27.7	30.1	28.1
8/15/16	Split-Soil Test	3	17.4	18.4	21.3	18.9	19.0
8/15/16	Split-Soil Test	4	14.4	12.0	13.9	14.4	13.7
8/15/16	Sensor	1	23.8	22.8	25.2	23.8	23.9
8/15/16	Sensor	2	21.3	21.3	20.3	18.9	20.5
8/15/16	Sensor	3	26.7	25.7	23.3	21.3	24.3
8/15/16	Sensor	4	19.8	16.9	22.3	24.3	20.8
8/15/16	Aerial NDVI	1	22.8	22.8	25.2	24.3	23.8
8/15/16	Aerial NDVI	2	24.7	24.3	23.3	25.2	24.4
8/15/16	Aerial NDVI	3	19.3	21.8	25.2	24.7	22.8
8/15/16	Aerial NDVI	4	18.4	16.4	18.9	22.3	19.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/23/16	Check	1	25.2	23.8	24.7	23.8	24.4
8/23/16	Check	2	24.7	26.2	23.8	26.2	25.2
8/23/16	Check	3	18.3	21.3	16.9	17.4	18.5
8/23/16	Check	4	22.8	24.7	20.8	18.9	21.8
8/23/16	Soil Test	1	20.8	18.4	23.3	22.8	21.3
8/23/16	Soil Test	2	29.2	27.2	28.2	28.2	28.2
8/23/16	Soil Test	3	19.8	20.8	29.8	23.3	23.4
8/23/16	Soil Test	4	23.3	24.7	23.3	16.4	21.9
8/23/16	Split-Soil Test	1	25.2	23.3	24.7	24.3	24.4
8/23/16	Split-Soil Test	2	31.1	28.2	28.2	27.2	28.7
8/23/16	Split-Soil Test	3	22.3	18.8	18.4	16.8	19.1
8/23/16	Split-Soil Test	4	13.5	10.0	12.0	15.9	12.9
8/23/16	Sensor	1	21.3	19.3	21.8	21.3	20.9
8/23/16	Sensor	2	24.7	22.8	21.8	22.8	23.0
8/23/16	Sensor	3	24.7	25.2	25.2	28.2	25.8
8/23/16	Sensor	4	24.9	22.8	18.4	21.3	21.9
8/23/16	Aerial NDVI	1	24.3	23.8	26.7	22.3	24.3
8/23/16	Aerial NDVI	2	26.7	28.7	26.7	25.2	26.8
8/23/16	Aerial NDVI	3	18.4	25.2	25.2	22.3	22.8
8/23/16	Aerial NDVI	4	18.9	15.9	18.9	21.3	18.8

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/21/16	Check	1	30.6	29.2	27.2	34.1	30.3
9/21/16	Check	2	27.7	28.2	29.7	28.7	28.6
9/21/16	Check	3	26.2	22.8	26.7	29.2	26.2
9/21/16	Check	4	30.1	24.7	26.2	27.7	27.2
9/21/16	Soil Test	1	31.1	29.2	26.2	32.1	29.7
9/21/16	Soil Test	2	31.6	31.6	30.1	31.1	31.1
9/21/16	Soil Test	3	29.7	24.3	27.2	28.7	27.5
9/21/16	Soil Test	4	27.2	27.7	26.7	28.7	27.6
9/21/16	Split-Soil Test	1	31.1	29.2	30.1	31.1	30.4
9/21/16	Split-Soil Test	2	30.1	29.2	29.2	31.1	29.9
9/21/16	Split-Soil Test	3	23.8	23.3	25.2	26.7	24.8
9/21/16	Split-Soil Test	4	26.2	20.3	22.3	25.2	23.5
9/21/16	Sensor	1	29.7	28.7	27.7	32.6	29.7
9/21/16	Sensor	2	26.7	26.7	28.2	29.2	27.7
9/21/16	Sensor	3	31.6	31.6	30.1	31.1	31.1
9/21/16	Sensor	4	29.7	22.3	25.2	28.7	26.5
9/21/16	Aerial NDVI	1	29.2	31.1	31.6	34.6	31.6
9/21/16	Aerial NDVI	2	28.7	26.7	28.7	30.1	28.6
9/21/16	Aerial NDVI	3	30.1	24.3	30.1	31.1	28.9
9/21/16	Aerial NDVI	4	28.2	22.3	23.8	28.7	25.8

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/27/16	Check	1	32.1	31.6	35.1	34.6	33.4
9/27/16	Check	2	30.6	29.2	30.1	29.7	29.9
9/27/16	Check	3	27.2	28.7	31.1	30.1	29.3
9/27/16	Check	4	30.1	30.1	28.7	28.2	29.3
9/27/16	Soil Test	1	34.6	33.6	31.6	32.1	33.0
9/27/16	Soil Test	2	32.1	32.6	32.6	30.1	31.9
9/27/16	Soil Test	3	29.2	26.2	27.2	30.1	28.2
9/27/16	Soil Test	4	28.7	29.7	29.7	29.2	29.3
9/27/16	Split-Soil Test	1	32.6	36.6	34.6	34.1	34.5
9/27/16	Split-Soil Test	2	32.6	30.6	35.1	33.1	32.9
9/27/16	Split-Soil Test	3	25.7	27.7	26.5	25.2	26.3
9/27/16	Split-Soil Test	4	27.7	24.3	24.8	21.7	24.6
9/27/16	Sensor	1	32.1	33.1	34.6	34.6	33.6
9/27/16	Sensor	2	30.1	30.1	30.1	28.7	29.8
9/27/16	Sensor	3	33.1	34.1	32.1	32.6	33.0
9/27/16	Sensor	4	29.7	27.2	28.2	29.2	28.6
9/27/16	Aerial NDVI	1	34.1	33.1	31.1	36.0	33.6
9/27/16	Aerial NDVI	2	30.1	31.1	30.1	25.2	29.1
9/27/16	Aerial NDVI	3	30.1	29.7	28.7	30.1	29.7
9/27/16	Aerial NDVI	4	26.7	27.2	28.2	30.1	28.1

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
10/14/16	Check	1	31.6	31.1	32.1	32.6	31.9
10/14/16	Check	2	29.7	27.2	27.2	30.1	28.6
10/14/16	Check	3	25.2	24.3	25.7	28.2	25.9
10/14/16	Check	4	30.6	23.8	22.3	28.2	26.2
10/14/16	Soil Test	1	31.6	30.1	28.7	28.2	29.7
10/14/16	Soil Test	2	30.6	31.6	31.1	31.6	31.2
10/14/16	Soil Test	3	29.2	24.7	30.1	28.7	28.2
10/14/16	Soil Test	4	30.6	27.7	28.2	29.7	29.1
10/14/16	Split-Soil Test	1	31.6	33.6	32.1	32.1	32.4
10/14/16	Split-Soil Test	2	32.1	31.1	32.1	32.1	31.9
10/14/16	Split-Soil Test	3	27.2	24.7	25.7	28.2	26.5
10/14/16	Split-Soil Test	4	27.7	23.3	24.3	26.2	25.4
10/14/16	Sensor	1	33.1	31.6	28.7	31.1	31.1
10/14/16	Sensor	2	26.2	29.2	29.2	27.7	28.1
10/14/16	Sensor	3	30.1	30.1	31.6	29.7	30.4
10/14/16	Sensor	4	25.7	24.7	26.2	28.7	26.3
10/14/16	Aerial NDVI	1	31.6	27.7	32.1	31.6	30.8
10/14/16	Aerial NDVI	2	30.1	30.6	29.7	29.2	29.9
10/14/16	Aerial NDVI	3	30.6	27.7	29.2	29.7	29.3
10/14/16	Aerial NDVI	4	25.7	25.2	25.7	29.7	26.6

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Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/8/17	Check	1	20.8	19.8	22.3	15.9	19.7
5/8/17	Check	2	19.8	18.4	20.8	14.9	18.5
5/8/17	Check	3	18.4	19.3	14.9	17.4	17.5
5/8/17	Check	4	16.9	16.9	15.9	16.4	16.5
5/8/17	Soil Test	1	18.9	21.3	14.4	11.5	16.5
5/8/17	Soil Test	2	19.3	20.3	16.4	16.4	18.1
5/8/17	Soil Test	3	16.4	18.9	20.8	16.4	18.1
5/8/17	Soil Test	4	20.8	17.4	18.9	16.9	18.5
5/8/17	Split-Soil Test	1	16.4	16.3	21.3	20.8	18.7
5/8/17	Split-Soil Test	2	18.4	21.3	14.4	18.4	18.1
5/8/17	Split-Soil Test	3	13.9	21.3	18.4	13.9	16.9
5/8/17	Split-Soil Test	4	19.3	13.0	17.4	22.3	18.0
5/8/17	Sensor	1	14.9	19.8	22.8	10.0	16.9
5/8/17	Sensor	2	19.8	18.4	18.4	18.9	18.9
5/8/17	Sensor	3	15.9	9.5	18.4	11.5	13.8
5/8/17	Sensor	4	22.8	17.4	19.3	16.9	19.1
5/8/17	Aerial NDVI	1	12.0	24.3	20.8	14.4	17.9
5/8/17	Aerial NDVI	2	18.9	8.5	17.5	19.3	16.1
5/8/17	Aerial NDVI	3	18.4	19.8	10.0	16.9	16.3
5/8/17	Aerial NDVI	4	20.8	19.8	16.4	14.9	18.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/15/17	Check	1	23.3	24.3	20.3	17.4	21.3
5/15/17	Check	2	20.8	16.9	20.3	18.9	19.2
5/15/17	Check	3	20.3	20.8	12.5	13.5	16.8
5/15/17	Check	4	20.3	18.4	13.5	19.8	18.0
5/15/17	Soil Test	1	22.8	16.9	18.4	20.8	19.7
5/15/17	Soil Test	2	16.4	14.9	14.9	18.4	16.2
5/15/17	Soil Test	3	19.3	18.4	15.9	16.4	17.5
5/15/17	Soil Test	4	21.8	19.8	18.4	19.8	20.0
5/15/17	Split-Soil Test	1	24.7	19.8	20.3	18.9	20.9
5/15/17	Split-Soil Test	2	24.7	18.9	23.3	25.2	23.0
5/15/17	Split-Soil Test	3	19.8	20.3	19.8	15.9	19.0
5/15/17	Split-Soil Test	4	20.3	22.3	14.4	19.3	19.1
5/15/17	Sensor	1	24.7	18.9	18.4	22.3	21.1
5/15/17	Sensor	2	19.8	17.4	14.4	18.4	17.5
5/15/17	Sensor	3	21.8	20.8	14.9	16.4	18.5
5/15/17	Sensor	4	20.8	11.5	10.5	16.9	14.9
5/15/17	Aerial NDVI	1	27.2	21.8	24.3	22.8	24.0
5/15/17	Aerial NDVI	2	19.3	20.3	16.4	20.8	19.2
5/15/17	Aerial NDVI	3	198.0	15.9	12.0	13.9	60.0
5/15/17	Aerial NDVI	4	19.3	15.4	18.4	11.5	16.2

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/24/17	Check	1	21.3	22.3	28.2	29.7	25.4
5/24/17	Check	2	31.6	29.2	27.7	27.2	28.9
5/24/17	Check	3	19.0	18.9	25.2	26.2	22.3
5/24/17	Check	4	23.8	26.7	19.8	20.8	22.8
5/24/17	Soil Test	1	25.2	28.2	29.2	29.2	28.0
5/24/17	Soil Test	2	30.1	28.7	22.8	20.8	25.6
5/24/17	Soil Test	3	21.3	19.3	22.8	24.7	22.0
5/24/17	Soil Test	4	24.3	22.8	22.8	24.3	23.6
5/24/17	Split-Soil Test	1	28.7	26.7	31.6	20.6	26.9
5/24/17	Split-Soil Test	2	29.7	29.2	29.7	29.7	29.6
5/24/17	Split-Soil Test	3	25.2	23.3	23.3	25.2	24.3
5/24/17	Split-Soil Test	4	24.3	22.8	22.8	21.8	22.9
5/24/17	Sensor	1	30.1	22.8	24.7	28.7	26.6
5/24/17	Sensor	2	26.7	29.2	27.7	27.2	27.7
5/24/17	Sensor	3	21.3	23.2	22.8	16.9	21.1
5/24/17	Sensor	4	26.7	16.9	19.8	16.9	20.1
5/24/17	Aerial NDVI	1	29.2	28.7	30.1	33.1	30.3
5/24/17	Aerial NDVI	2	21.8	29.2	29.2	25.7	26.5
5/24/17	Aerial NDVI	3	23.8	24.7	27.7	24.7	25.2
5/24/17	Aerial NDVI	4	26.2	18.9	18.9	23.8	22.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/29/17	Check	1	21.8	27.2	28.2	22.3	24.9
5/29/17	Check	2	32.6	31.1	28.2	29.2	30.3
5/29/17	Check	3	25.2	22.8	18.9	19.8	21.7
5/29/17	Check	4	24.3	23.3	18.4	19.3	21.3
5/29/17	Soil Test	1	27.7	27.7	22.8	22.3	25.1
5/29/17	Soil Test	2	28.7	28.7	20.8	24.7	25.7
5/29/17	Soil Test	3	23.8	25.2	21.3	22.8	23.3
5/29/17	Soil Test	4	22.3	21.8	23.3	19.3	21.7
5/29/17	Split-Soil Test	1	30.1	27.2	23.3	26.7	26.8
5/29/17	Split-Soil Test	2	32.6	29.2	32.1	28.7	30.7
5/29/17	Split-Soil Test	3	21.3	22.8	19.8	20.8	21.2
5/29/17	Split-Soil Test	4	21.3	22.3	18.4	19.8	20.5
5/29/17	Sensor	1	30.6	28.2	23.3	23.3	26.4
5/29/17	Sensor	2	31.6	20.1	28.2	29.7	27.4
5/29/17	Sensor	3	22.3	21.3	17.9	18.4	20.0
5/29/17	Sensor	4	24.3	22.3	15.4	15.4	19.4
5/29/17	Aerial NDVI	1	24.7	28.2	26.7	22.3	25.5
5/29/17	Aerial NDVI	2	28.2	24.7	24.7	23.8	25.4
5/29/17	Aerial NDVI	3	24.3	24.3	22.8	21.3	23.2
5/29/17	Aerial NDVI	4	23.3	21.6	13.9	17.9	19.2

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/5/17	Check	1	23.3	20.3	13.5	14.4	17.9
6/5/17	Check	2	19.3	22.3	24.3	18.4	21.1
6/5/17	Check	3	13.0	18.9	18.9	11.5	15.6
6/5/17	Check	4	13.5	21.8	12.5	18.4	16.6
6/5/17	Soil Test	1	10.9	19.3	169.0	18.9	54.5
6/5/17	Soil Test	2	18.4	16.4	19.3	14.4	17.1
6/5/17	Soil Test	3	18.4	17.4	13.9	18.9	17.2
6/5/17	Soil Test	4	16.9	15.9	15.4	13.0	15.3
6/5/17	Split-Soil Test	1	15.9	19.8	18.4	15.9	17.5
6/5/17	Split-Soil Test	2	23.8	19.8	22.3	21.8	21.9
6/5/17	Split-Soil Test	3	14.9	17.4	16.9	14.9	16.0
6/5/17	Split-Soil Test	4	16.4	14.9	16.9	13.9	15.5
6/5/17	Sensor	1	15.1	20.3	22.3	18.4	19.0
6/5/17	Sensor	2	18.9	21.8	21.3	18.9	20.2
6/5/17	Sensor	3	14.4	18.4	15.4	11.5	14.9
6/5/17	Sensor	4	13.9	18.4	15.4	11.5	14.8
6/5/17	Aerial NDVI	1	15.9	17.4	22.8	18.9	18.8
6/5/17	Aerial NDVI	2	18.4	19.8	18.9	16.9	18.5
6/5/17	Aerial NDVI	3	19.3	16.9	15.4	13.9	16.4
6/5/17	Aerial NDVI	4	10.5	15.9	11.5	15.9	13.5

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/12/17	Check	1	14.4	13.5	9.5	8.5	11.5
6/12/17	Check	2	14.4	11.5	14.9	15.4	14.1
6/12/17	Check	3	7.1	12.5	11.0	5.1	8.9
6/12/17	Check	4	9.5	7.1	10.5	17.9	11.3
6/12/17	Soil Test	1	7.1	12.0	15.4	11.0	11.4
6/12/17	Soil Test	2	9.0	9.0	7.6	7.1	8.2
6/12/17	Soil Test	3	8.5	9.5	6.6	9.5	8.5
6/12/17	Soil Test	4	8.5	8.5	9.0	9.0	8.8
6/12/17	Split-Soil Test	1	15.4	12.0	7.6	9.5	11.1
6/12/17	Split-Soil Test	2	10.5	13.5	13.5	11.0	12.1
6/12/17	Split-Soil Test	3	9.0	10.5	13.9	9.5	10.7
6/12/17	Split-Soil Test	4	8.5	11.5	8.5	6.6	8.8
6/12/17	Sensor	1	19.8	16.4	7.1	11.0	13.6
6/12/17	Sensor	2	10.5	11.5	11.5	12.0	11.4
6/12/17	Sensor	3	14.4	9.0	11.0	7.0	10.4
6/12/17	Sensor	4	10.0	9.0	5.1	5.1	7.3
6/12/17	Aerial NDVI	1	13.0	15.4	9.0	12.0	12.4
6/12/17	Aerial NDVI	2	11.5	11.0	9.5	8.5	10.1
6/12/17	Aerial NDVI	3	14.4	12.5	8.5	7.6	10.8
6/12/17	Aerial NDVI	4	7.1	0.1	9.5	9.5	6.6

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/19/17	Check	1	7.6	9.2	11.5	8.1	9.1
6/19/17	Check	2	9.5	8.1	10.0	9.0	9.2
6/19/17	Check	3	8.1	3.5	4.1	3.6	4.8
6/19/17	Check	4	8.5	6.1	9.0	13.5	9.3
6/19/17	Soil Test	1	8.5	11.5	8.5	6.6	8.8
6/19/17	Soil Test	2	6.6	4.1	4.6	6.1	5.4
6/19/17	Soil Test	3	5.1	3.6	4.6	4.1	4.4
6/19/17	Soil Test	4	5.1	7.1	5.6	5.1	5.7
6/19/17	Split-Soil Test	1	10.0	9.0	5.6	9.5	8.5
6/19/17	Split-Soil Test	2	9.5	9.5	6.6	6.6	8.1
6/19/17	Split-Soil Test	3	9.5	5.6	5.1	5.1	6.3
6/19/17	Split-Soil Test	4	7.1	5.6	6.1	7.1	6.5
6/19/17	Sensor	1	13.0	6.6	5.1	10.5	8.8
6/19/17	Sensor	2	7.1	9.0	6.6	6.6	7.3
6/19/17	Sensor	3	7.6	5.1	4.6	6.1	5.9
6/19/17	Sensor	4	7.1	4.1	4.6	8.1	6.0
6/19/17	Aerial NDVI	1	11.0	11.0	4.6	7.1	8.4
6/19/17	Aerial NDVI	2	6.6	6.6	5.6	6.6	6.4
6/19/17	Aerial NDVI	3	8.1	7.1	5.1	8.5	7.2
6/19/17	Aerial NDVI	4	5.1	5.1	9.0	6.1	6.3

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/26/17	Check	1	5.1	5.1	7.1	5.1	5.6
6/26/17	Check	2	7.6	9.0	9.0	8.5	8.5
6/26/17	Check	3	7.6	8.1	6.1	5.6	6.9
6/26/17	Check	4	9.5	6.6	6.6	10.0	8.2
6/26/17	Soil Test	1	6.6	8.5	8.0	7.6	7.7
6/26/17	Soil Test	2	5.6	6.6	4.6	4.6	5.4
6/26/17	Soil Test	3	10.0	6.1	8.5	6.6	7.8
6/26/17	Soil Test	4	8.5	8.1	4.6	4.6	6.5
6/26/17	Split-Soil Test	1	6.1	11.0	5.6	5.6	7.1
6/26/17	Split-Soil Test	2	9.5	10.5	10.0	11.5	10.4
6/26/17	Split-Soil Test	3	5.6	4.5	8.5	7.6	6.6
6/26/17	Split-Soil Test	4	9.5	8.5	7.1	8.1	8.3
6/26/17	Sensor	1	6.6	5.1	5.6	5.6	5.7
6/26/17	Sensor	2	6.6	7.6	6.1	8.5	7.2
6/26/17	Sensor	3	6.6	6.6	5.1	7.1	6.4
6/26/17	Sensor	4	8.1	7.6	5.1	5.1	6.5
6/26/17	Aerial NDVI	1	6.6	7.5	8.1	10.0	8.1
6/26/17	Aerial NDVI	2	8.1	6.6	6.6	6.6	7.0
6/26/17	Aerial NDVI	3	10.0	10.0	6.6	5.6	8.1
6/26/17	Aerial NDVI	4	8.1	6.1	8.1	8.5	7.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/3/17	Check	1	23.3	23.8	26.7	27.7	25.4
7/3/17	Check	2	21.8	24.7	31.6	32.6	27.7
7/3/17	Check	3	17.7	13.4	14.8	13.5	14.9
7/3/17	Check	4	13.4	14.4	16.4	15.4	14.9
7/3/17	Soil Test	1	23.8	23.3	20.8	18.4	21.6
7/3/17	Soil Test	2	15.8	16.9	25.7	16.4	18.7
7/3/17	Soil Test	3	10.3	10.7	10.6	10.9	10.6
7/3/17	Soil Test	4	10.4	10.5	10.4	10.7	10.5
7/3/17	Split-Soil Test	1	20.3	22.8	26.7	24.7	23.6
7/3/17	Split-Soil Test	2	14.4	22.8	24.7	28.8	22.7
7/3/17	Split-Soil Test	3	10.6	10.4	9.9	9.8	10.2
7/3/17	Split-Soil Test	4	10.2	10.2	10.2	10.3	10.2
7/3/17	Sensor	1	15.4	22.8	18.9	21.3	19.6
7/3/17	Sensor	2	32.1	26.7	29.2	27.2	28.8
7/3/17	Sensor	3	12.3	11.4	10.7	10.4	11.2
7/3/17	Sensor	4	10.5	11.0	7.5	10.0	9.8
7/3/17	Aerial NDVI	1	22.3	20.8	22.3	26.2	22.9
7/3/17	Aerial NDVI	2	27.1	23.8	26.5	25.2	25.7
7/3/17	Aerial NDVI	3	10.6	10.1	10.3	10.5	10.4
7/3/17	Aerial NDVI	4	10.5	11.5	13.6	9.5	11.3

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/10/17	Check	1	13.9	15.4	10.0	10.0	12.3
7/10/17	Check	2	17.4	16.9	13.9	16.4	16.2
7/10/17	Check	3	12.0	10.0	7.1	7.1	9.1
7/10/17	Check	4	10.5	7.6	7.1	7.1	8.1
7/10/17	Soil Test	1	11.5	10.0	9.0	8.1	9.7
7/10/17	Soil Test	2	14.1	15.9	9.0	7.6	11.7
7/10/17	Soil Test	3	7.1	7.1	4.6	5.6	6.1
7/10/17	Soil Test	4	5.6	4.6	4.1	3.1	4.4
7/10/17	Split-Soil Test	1	8.1	11.5	8.5	10.0	9.5
7/10/17	Split-Soil Test	2	17.9	19.3	13.9	14.9	16.5
7/10/17	Split-Soil Test	3	5.6	7.1	5.6	4.6	5.7
7/10/17	Split-Soil Test	4	5.6	5.6	5.6	5.6	5.6
7/10/17	Sensor	1	10.5	9.5	4.6	8.1	8.2
7/10/17	Sensor	2	17.4	12.9	15.9	13.9	15.0
7/10/17	Sensor	3	8.5	7.1	4.6	5.6	6.5
7/10/17	Sensor	4	5.5	6.1	4.1	4.1	5.0
7/10/17	Aerial NDVI	1	12.5	13.9	12.5	10.0	12.2
7/10/17	Aerial NDVI	2	13.0	16.9	10.5	12.5	13.2
7/10/17	Aerial NDVI	3	12.5	14.4	10.5	7.7	11.3
7/10/17	Aerial NDVI	4	5.1	6.1	7.1	9.0	6.8

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/17/17	Check	1	3.1	4.1	6.1	4.1	4.4
7/17/17	Check	2	8.5	7.6	9.0	9.0	8.5
7/17/17	Check	3	4.1	3.1	4.6	3.6	3.9
7/17/17	Check	4	3.6	4.6	9.0	3.1	5.1
7/17/17	Soil Test	1	4.6	4.6	3.1	4.6	4.2
7/17/17	Soil Test	2	5.6	8.5	5.1	4.1	5.8
7/17/17	Soil Test	3	3.6	3.1	3.1	3.1	3.2
7/17/17	Soil Test	4	3.6	3.6	3.1	4.6	3.7
7/17/17	Split-Soil Test	1	4.1	3.6	3.6	5.1	4.1
7/17/17	Split-Soil Test	2	7.1	6.1	7.6	7.1	7.0
7/17/17	Split-Soil Test	3	3.6	3.6	3.6	3.6	3.6
7/17/17	Split-Soil Test	4	3.6	3.6	2.4	3.6	3.3
7/17/17	Sensor	1	5.1	4.1	4.1	3.6	4.2
7/17/17	Sensor	2	7.6	9.0	6.1	7.6	7.6
7/17/17	Sensor	3	3.1	3.6	3.6	3.1	3.4
7/17/17	Sensor	4	3.6	4.1	3.6	3.1	3.6
7/17/17	Aerial NDVI	1	5.6	5.6	5.1	3.6	5.0
7/17/17	Aerial NDVI	2	5.6	6.6	7.6	5.6	6.4
7/17/17	Aerial NDVI	3	4.6	6.1	4.1	4.6	4.9
7/17/17	Aerial NDVI	4	3.6	3.1	2.4	3.6	3.2

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/24/17	Check	1	12.5	12.0	9.0	9.0	10.6
7/24/17	Check	2	15.9	13.5	12.5	13.5	13.9
7/24/17	Check	3	10.5	11.5	7.6	7.6	9.3
7/24/17	Check	4	12.0	85.0	8.5	6.6	28.0
7/24/17	Soil Test	1	12.5	13.0	9.5	9.5	11.1
7/24/17	Soil Test	2	12.5	13.0	5.6	7.6	9.7
7/24/17	Soil Test	3	12.5	11.5	6.6	9.0	9.9
7/24/17	Soil Test	4	9.5	9.0	8.5	8.1	8.8
7/24/17	Split-Soil Test	1	11.0	13.5	11.0	10.5	11.5
7/24/17	Split-Soil Test	2	14.0	17.5	13.5	12.0	14.3
7/24/17	Split-Soil Test	3	12.0	12.0	13.0	14.4	12.9
7/24/17	Split-Soil Test	4	10.5	13.5	11.0	11.0	11.5
7/24/17	Sensor	1	11.0	13.9	13.5	12.0	12.6
7/24/17	Sensor	2	10.5	9.0	11.0	11.0	10.4
7/24/17	Sensor	3	10.5	13.0	9.5	10.5	10.9
7/24/17	Sensor	4	13.9	10.5	8.5	6.6	9.9
7/24/17	Aerial NDVI	1	9.0	9.0	8.5	13.0	9.9
7/24/17	Aerial NDVI	2	13.5	14.9	9.0	10.5	12.0
7/24/17	Aerial NDVI	3	12.0	10.5	8.1	10.0	10.2
7/24/17	Aerial NDVI	4	7.1	8.1	10.0	9.0	8.6

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/1/2017	Check	1	23.2	20.8	16.9	16.4	19.3
8/1/2017	Check	2	20.3	20.8	18.4	17.4	19.2
8/1/2017	Check	3	15.4	18.4	13.0	12.0	14.7
8/1/2017	Check	4	14.9	13.0	12.0	9.0	12.2
8/1/2017	Soil Test	1	19.8	19.3	19.4	17.4	19.0
8/1/2017	Soil Test	2	16.9	14.4	9.5	9.5	12.6
8/1/2017	Soil Test	3	14.9	14.9	13.9	13.9	14.4
8/1/2017	Soil Test	4	12.5	13.0	12.5	10.5	12.1
8/1/2017	Split-Soil Test	1	20.3	18.4	17.9	17.4	18.5
8/1/2017	Split-Soil Test	2	16.9	18.4	17.9	19.8	18.3
8/1/2017	Split-Soil Test	3	16.9	15.4	17.4	16.9	16.7
8/1/2017	Split-Soil Test	4	14.4	13.0	13.0	13.5	13.5
8/1/2017	Sensor	1	24.3	16.9	10.5	20.3	18.0
8/1/2017	Sensor	2	20.5	18.4	19.9	17.4	19.1
8/1/2017	Sensor	3	15.4	13.9	11.5	12.0	13.2
8/1/2017	Sensor	4	17.9	14.0	10.0	9.5	12.9
8/1/2017	Aerial NDVI	1	22.8	19.8	13.0	16.9	18.1
8/1/2017	Aerial NDVI	2	20.2	21.3	13.5	13.5	17.1
8/1/2017	Aerial NDVI	3	17.4	14.4	16.4	13.5	15.4
8/1/2017	Aerial NDVI	4	16.4	13.5	10.0	10.0	12.5

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/8/17	Check	1	35.1	37.5	36.0	29.2	34.5
8/8/17	Check	2	39.0	37.0	37.5	33.7	36.8
8/8/17	Check	3	27.7	29.2	29.2	29.7	29.0
8/8/17	Check	4	27.2	28.2	27.2	24.3	26.7
8/8/17	Soil Test	1	30.6	32.1	33.1	27.7	30.9
8/8/17	Soil Test	2	31.6	33.1	23.6	24.7	28.3
8/8/17	Soil Test	3	25.7	25.2	24.3	22.3	24.4
8/8/17	Soil Test	4	20.8	20.5	21.8	19.4	20.6
8/8/17	Split-Soil Test	1	33.6	33.6	31.6	26.2	31.3
8/8/17	Split-Soil Test	2	35.1	34.1	33.1	36.5	34.7
8/8/17	Split-Soil Test	3	24.3	24.7	24.3	23.9	24.3
8/8/17	Split-Soil Test	4	23.8	24.7	23.3	23.3	23.8
8/8/17	Sensor	1	33.6	31.6	34.1	25.2	31.1
8/8/17	Sensor	2	34.6	38.0	38.0	39.1	37.4
8/8/17	Sensor	3	24.3	27.7	26.7	27.7	26.6
8/8/17	Sensor	4	23.3	25.2	24.7	21.8	23.8
8/8/17	Aerial NDVI	1	34.6	34.6	34.1	29.2	33.1
8/8/17	Aerial NDVI	2	32.1	34.6	23.1	30.6	30.1
8/8/17	Aerial NDVI	3	30.6	32.1	30.6	37.5	32.7
8/8/17	Aerial NDVI	4	34.6	25.7	20.8	18.3	24.9

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/14/17	Check	1	26.7	23.8	23.8	29.2	25.9
8/14/17	Check	2	30.6	30.6	30.1	30.6	30.5
8/14/17	Check	3	21.3	25.2	16.4	15.4	19.6
8/14/17	Check	4	19.8	19.3	13.5	12.5	16.3
8/14/17	Soil Test	1	21.3	10.8	20.3	20.3	18.2
8/14/17	Soil Test	2	25.7	26.2	20.3	21.3	23.4
8/14/17	Soil Test	3	19.0	19.8	15.9	15.4	17.5
8/14/17	Soil Test	4	10.9	13.9	12.5	14.4	12.9
8/14/17	Split-Soil Test	1	26.7	27.2	20.3	25.2	24.9
8/14/17	Split-Soil Test	2	26.2	26.6	27.2	28.2	27.1
8/14/17	Split-Soil Test	3	18.9	12.4	14.4	13.9	14.9
8/14/17	Split-Soil Test	4	16.9	19.8	20.3	20.3	19.3
8/14/17	Sensor	1	24.2	24.7	22.8	21.8	23.4
8/14/17	Sensor	2	21.1	31.1	29.7	27.7	27.4
8/14/17	Sensor	3	19.8	14.8	13.5	15.9	16.0
8/14/17	Sensor	4	12.4	16.9	11.5	13.5	13.6
8/14/17	Aerial NDVI	1	27.2	.	.	.	27.2
8/14/17	Aerial NDVI	2	24.3	26.2	26.7	26.7	26.0
8/14/17	Aerial NDVI	3	19.8	25.2	18.9	20.8	21.2
8/14/17	Aerial NDVI	4	15.9	22.3	13.5	10.5	15.6

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/23/17	Check	1	25.3	24.3	15.9	22.8	22.1
8/23/17	Check	2	20.3	23.8	22.8	23.8	22.7
8/23/17	Check	3	18.9	16.4	13.0	13.5	15.5
8/23/17	Check	4	16.4	15.4	12.0	13.0	14.2
8/23/17	Soil Test	1	20.8	21.3	17.4	18.4	19.5
8/23/17	Soil Test	2	23.8	22.8	18.4	20.8	21.5
8/23/17	Soil Test	3	10.5	13.0	14.9	14.4	13.2
8/23/17	Soil Test	4	12.0	12.5	13.0	11.5	12.3
8/23/17	Split-Soil Test	1	18.4	16.4	17.4	19.3	17.9
8/23/17	Split-Soil Test	2	24.7	21.8	20.8	20.8	22.0
8/23/17	Split-Soil Test	3	11.5	13.0	14.9	13.0	13.1
8/23/17	Split-Soil Test	4	13.0	13.0	10.5	13.9	12.6
8/23/17	Sensor	1	16.4	20.3	11.5	15.9	16.0
8/23/17	Sensor	2	24.7	26.2	21.3	22.3	23.6
8/23/17	Sensor	3	11.5	12.5	11.0	10.5	11.4
8/23/17	Sensor	4	8.5	8.5	13.0	10.0	10.0
8/23/17	Aerial NDVI	1	20.8	20.8	15.9	20.3	19.5
8/23/17	Aerial NDVI	2	30.1	25.7	20.3	21.3	24.4
8/23/17	Aerial NDVI	3	16.4	15.4	12.0	13.0	14.2
8/23/17	Aerial NDVI	4	18.4	12.0	9.5	9.5	12.4

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/30/17	Check	1	25.2	24.3	15.9	22.8	22.1
8/30/17	Check	2	20.3	23.8	22.8	23.8	22.7
8/30/17	Check	3	18.9	16.4	13.0	13.5	15.5
8/30/17	Check	4	16.4	15.4	12.0	13.0	14.2
8/30/17	Soil Test	1	20.8	21.3	17.4	18.4	19.5
8/30/17	Soil Test	2	23.8	22.8	18.4	20.8	21.5
8/30/17	Soil Test	3	10.5	13.0	14.9	14.4	13.2
8/30/17	Soil Test	4	12.0	12.5	13.0	11.5	12.3
8/30/17	Split-Soil Test	1	18.4	16.4	17.4	19.3	17.9
8/30/17	Split-Soil Test	2	24.7	21.8	20.8	20.8	22.0
8/30/17	Split-Soil Test	3	11.5	13.0	14.9	13.0	13.1
8/30/17	Split-Soil Test	4	13.0	13.0	10.5	13.9	12.6
8/30/17	Sensor	1	16.4	20.3	11.5	15.9	16.0
8/30/17	Sensor	2	24.7	26.2	21.3	22.3	23.6
8/30/17	Sensor	3	11.5	12.5	11.0	10.5	11.4
8/30/17	Sensor	4	8.5	8.5	13.0	10.0	10.0
8/30/17	Aerial NDVI	1	20.8	20.8	15.9	20.3	19.5
8/30/17	Aerial NDVI	2	30.1	25.7	20.3	21.3	24.4
8/30/17	Aerial NDVI	3	16.4	13.9	15.9	13.0	14.8
8/30/17	Aerial NDVI	4	19.4	12.0	9.5	9.5	12.6

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/6/17	Check	1	16.9	15.9	13.0	13.5	14.8
9/6/17	Check	2	15.9	15.9	14.9	14.4	15.3
9/6/17	Check	3	13.0	10.5	10.0	11.0	11.1
9/6/17	Check	4	12.0	12.0	8.1	8.1	10.1
9/6/17	Soil Test	1	13.5	13.0	12.5	11.5	12.6
9/6/17	Soil Test	2	14.9	14.9	9.5	11.0	12.6
9/6/17	Soil Test	3	10.0	9.5	97.6	12.0	32.3
9/6/17	Soil Test	4	6.6	8.1	7.6	5.6	7.0
9/6/17	Split-Soil Test	1	14.4	11.0	11.0	12.5	12.2
9/6/17	Split-Soil Test	2	17.4	15.4	12.5	13.9	14.8
9/6/17	Split-Soil Test	3	9.0	6.6	9.0	5.1	7.4
9/6/17	Split-Soil Test	4	8.1	7.6	9.0	8.5	8.3
9/6/17	Sensor	1	13.9	13.9	10.0	10.5	12.1
9/6/17	Sensor	2	15.9	15.9	13.9	13.9	14.9
9/6/17	Sensor	3	8.1	10.0	7.1	7.6	8.2
9/6/17	Sensor	4	5.1	3.6	6.6	6.6	5.5
9/6/17	Aerial NDVI	1	14.9	13.5	12.0	13.0	13.4
9/6/17	Aerial NDVI	2	14.9	13.0	13.5	13.5	13.7
9/6/17	Aerial NDVI	3	9.0	9.5	8.1	9.5	9.0
9/6/17	Aerial NDVI	4	10.0	6.6	4.1	8.1	7.2

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/13/17	Check	1	14.4	14.9	11.5	10.5	12.8
9/13/17	Check	2	14.9	14.4	12.0	13.0	13.6
9/13/17	Check	3	11.5	11.5	5.1	10.0	9.5
9/13/17	Check	4	8.5	10.0	8.1	9.5	9.0
9/13/17	Soil Test	1	12.5	11.0	8.1	8.1	9.9
9/13/17	Soil Test	2	13.0	12.5	8.5	9.5	10.9
9/13/17	Soil Test	3	9.0	9.5	6.1	7.6	8.1
9/13/17	Soil Test	4	6.1	5.5	5.6	5.6	5.7
9/13/17	Split-Soil Test	1	11.0	6.6	7.6	11.0	9.1
9/13/17	Split-Soil Test	2	14.9	14.9	9.0	12.5	12.8
9/13/17	Split-Soil Test	3	6.6	7.1	8.1	5.1	6.7
9/13/17	Split-Soil Test	4	7.6	7.1	7.1	6.6	7.1
9/13/17	Sensor	1	10.5	10.0	6.6	10.0	9.3
9/13/17	Sensor	2	13.9	14.4	11.5	13.5	13.3
9/13/17	Sensor	3	7.6	10.0	6.6	9.0	8.3
9/13/17	Sensor	4	6.1	6.6	5.1	4.1	5.5
9/13/17	Aerial NDVI	1	13.0	11.5	11.0	12.0	11.9
9/13/17	Aerial NDVI	2	12.5	11.5	8.5	11.0	10.9
9/13/17	Aerial NDVI	3	9.0	8.5	7.1	7.1	7.9
9/13/17	Aerial NDVI	4	8.5	6.6	5.6	6.1	6.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
10/1/17	Check	1	13.5	11.5	15.6	18.4	14.75
10/1/17	Check	2	13	16.9	15.9	13.4	14.8
10/1/17	Check	3	14.4	19.9	11.5	12	14.45
10/1/17	Check	4	13	8.1	10.5	11	10.65
10/1/17	Soil Test	1	15.9	13.5	10	9	12.1
10/1/17	Soil Test	2	11	11.5	13.5	15.9	12.975
10/1/17	Soil Test	3	13.5	13	11.5	14.9	13.225
10/1/17	Soil Test	4	6.1	9.5	5	7.1	6.925
10/1/17	Split-Soil Test	1	14.9	17.4	15.9	16.5	16.175
10/1/17	Split-Soil Test	2	20.3	15.4	15.9	13.3	16.225
10/1/17	Split-Soil Test	3	15.9	15.9	11.5	10.5	13.45
10/1/17	Split-Soil Test	4	10.5	14.9	11.5	13	12.475
10/1/17	Sensor	1	10	12	14.4	15.4	12.95
10/1/17	Sensor	2	13	14.4	15.9	14.9	14.55
10/1/17	Sensor	3	13	10.5	11.5	13.5	12.125
10/1/17	Sensor	4	9	11	11.5	8.3	9.95
10/1/17	Aerial NDVI	1	12.5	11.5	15.9	15.9	13.95
10/1/17	Aerial NDVI	2	13.9	10.5	12	13.5	12.475
10/1/17	Aerial NDVI	3	14.9	13	10	11.5	12.35
10/1/17	Aerial NDVI	4	15.9	11.5	18.9	11.5	14.45

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Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/9/17	Check	1	31.5	35.4	40.4	40.1	36.9
5/9/17	Check	2	20.2	26.5	24.5	37.4	27.2
5/9/17	Check	3	34.4	36.8	26.8	27.1	31.3
5/9/17	Check	4	34.1	40.4	26.8	21.5	30.7
5/9/17	Soil Test	1	54.7	62.1	59.6	45.9	55.6
5/9/17	Soil Test	2	41.7	44.1	47.4	33.4	41.7
5/9/17	Soil Test	3	28.1	33.1	29.5	27.5	29.6
5/9/17	Soil Test	4	36.4	34.8	29.1	29.5	32.5
5/9/17	Split-Soil Test	1	40.7	42.4	34.1	40.7	39.5
5/9/17	Split-Soil Test	2	29.5	35.8	30.5	36.4	33.1
5/9/17	Split-Soil Test	3	34.4	20.8	23.8	33.8	28.2
5/9/17	Split-Soil Test	4	39.1	36.1	21.8	35.4	33.1
5/9/17	Sensor	1	29.8	35.1	37.8	34.8	34.4
5/9/17	Sensor	2	34.8	29.8	22.8	39.7	31.8
5/9/17	Sensor	3	33.1	28.1	29.8	33.1	31.0
5/9/17	Sensor	4	31.5	22.2	36.1	35.4	31.3
5/9/17	Aerial NDVI	1	33.1	37.8	27.8	34.8	33.4
5/9/17	Aerial NDVI	2	38.4	35.4	36.1	32.1	35.5
5/9/17	Aerial NDVI	3	23.5	19.2	40.7	31.1	28.6
5/9/17	Aerial NDVI	4	36.1	26.1	38.7	31.1	33.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/16/17	Check	1	53.7	40.9	43.4	50.8	47.2
5/16/17	Check	2	40.0	51.7	44.4	29.2	41.3
5/16/17	Check	3	42.4	34.6	22.8	54.7	38.6
5/16/17	Check	4	57.1	50.8	37.5	28.7	43.5
5/16/17	Soil Test	1	50.3	54.2	50.8	48.3	50.9
5/16/17	Soil Test	2	52.5	34.6	38.0	32.6	39.4
5/16/17	Soil Test	3	42.9	41.4	44.4	37.5	41.6
5/16/17	Soil Test	4	44.9	33.1	42.4	38.2	39.7
5/16/17	Split-Soil Test	1	35.5	40.9	46.3	38.5	40.3
5/16/17	Split-Soil Test	2	36.5	32.1	50.3	41.4	40.1
5/16/17	Split-Soil Test	3	50.3	33.6	17.9	25.2	31.8
5/16/17	Split-Soil Test	4	51.7	34.6	20.3	48.8	38.9
5/16/17	Sensor	1	41.4	36.0	37.5	33.1	37.0
5/16/17	Sensor	2	29.2	37.0	42.9	32.6	35.4
5/16/17	Sensor	3	40.5	33.6	45.4	25.7	36.3
5/16/17	Sensor	4	38.0	41.4	26.2	49.8	38.9
5/16/17	Aerial NDVI	1	38.0	40.4	43.9	40.0	40.6
5/16/17	Aerial NDVI	2	44.4	45.9	42.4	43.4	44.0
5/16/17	Aerial NDVI	3	34.6	43.6	30.1	51.7	40.0
5/16/17	Aerial NDVI	4	29.7	44.4	40.5	28.2	35.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
5/24/17	Check	1	31.3	34.4	34.8	27.8	32.1
5/24/17	Check	2	30.8	28.8	23.8	25.5	27.2
5/24/17	Check	3	28.8	30.5	27.5	27.8	28.7
5/24/17	Check	4	34.4	36.4	28.8	32.1	32.9
5/24/17	Soil Test	1	37.1	31.5	33.1	32.1	33.5
5/24/17	Soil Test	2	31.5	32.8	31.1	27.1	30.6
5/24/17	Soil Test	3	29.1	36.4	34.1	23.8	30.9
5/24/17	Soil Test	4	30.8	35.8	32.1	33.1	33.0
5/24/17	Split-Soil Test	1	31.5	31.8	29.1	29.5	30.5
5/24/17	Split-Soil Test	2	29.1	23.1	26.1	30.8	27.3
5/24/17	Split-Soil Test	3	30.5	31.8	25.5	20.8	27.2
5/24/17	Split-Soil Test	4	27.8	31.8	27.1	20.5	26.8
5/24/17	Sensor	1	29.8	30.8	30.8	28.1	29.9
5/24/17	Sensor	2	26.5	24.8	26.8	27.8	26.5
5/24/17	Sensor	3	27.8	29.5	24.1	21.5	25.7
5/24/17	Sensor	4	29.8	26.8	25.5	27.1	27.3
5/24/17	Aerial NDVI	1	30.1	30.5	27.8	29.1	29.4
5/24/17	Aerial NDVI	2	30.5	31.1	28.8	26.8	29.3
5/24/17	Aerial NDVI	3	25.5	23.2	23.2	31.8	25.9
5/24/17	Aerial NDVI	4	32.4	24.5	31.1	30.8	29.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/6/17	Check	1	40.4	44.4	39.4	43.1	41.8
6/6/17	Check	2	37.4	29.1	33.8	43.1	35.9
6/6/17	Check	3	36.4	37.8	42.4	33.4	37.5
6/6/17	Check	4	43.4	40.4	31.5	43.7	39.8
6/6/17	Soil Test	1	46.4	42.4	45.4	41.1	43.8
6/6/17	Soil Test	2	44.4	39.1	44.4	41.1	42.3
6/6/17	Soil Test	3	41.1	41.7	46.4	35.8	41.3
6/6/17	Soil Test	4	41.7	34.8	35.8	38.7	37.8
6/6/17	Split-Soil Test	1	39.7	32.1	40.1	40.4	38.1
6/6/17	Split-Soil Test	2	34.8	38.7	34.4	37.8	36.4
6/6/17	Split-Soil Test	3	32.1	33.8	40.4	41.1	36.9
6/6/17	Split-Soil Test	4	46.4	31.1	31.1	33.4	35.5
6/6/17	Sensor	1	38.1	52.1	37.8	34.4	40.6
6/6/17	Sensor	2	35.1	33.1	32.4	31.8	33.1
6/6/17	Sensor	3	39.1	21.0	40.1	36.8	34.3
6/6/17	Sensor	4	38.7	35.8	37.8	33.8	36.5
6/6/17	Aerial NDVI	1	33.8	32.1	39.7	33.1	34.7
6/6/17	Aerial NDVI	2	40.1	38.7	40.7	37.1	39.2
6/6/17	Aerial NDVI	3	38.4	41.7	31.3	32.1	35.9
6/6/17	Aerial NDVI	4	41.1	32.2	34.1	38.7	36.5

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/13/17	Check	1	37.1	38.0	42.1	37.1	38.6
6/13/17	Check	2	35.1	18.9	21.5	17.9	23.4
6/13/17	Check	3	29.8	27.5	30.5	28.8	29.2
6/13/17	Check	4	39.7	37.4	21.5	31.1	32.4
6/13/17	Soil Test	1	26.8	23.8	33.4	30.8	28.7
6/13/17	Soil Test	2	32.1	37.8	31.1	18.9	30.0
6/13/17	Soil Test	3	30.5	25.5	24.2	33.4	28.4
6/13/17	Soil Test	4	25.5	35.8	32.8	25.2	29.8
6/13/17	Split-Soil Test	1	32.4	35.3	32.0	24.7	31.1
6/13/17	Split-Soil Test	2	31.1	31.5	29.5	20.0	28.0
6/13/17	Split-Soil Test	3	19.8	26.5	31.8	26.1	26.1
6/13/17	Split-Soil Test	4	31.8	29.5	31.1	40.1	33.1
6/13/17	Sensor	1	30.5	25.2	26.2	29.2	27.8
6/13/17	Sensor	2	28.8	29.5	25.8	23.5	26.9
6/13/17	Sensor	3	35.8	32.4	24.2	26.8	29.8
6/13/17	Sensor	4	32.1	28.1	25.5	25.2	27.7
6/13/17	Aerial NDVI	1	30.1	25.5	29.1	24.5	27.3
6/13/17	Aerial NDVI	2	32.8	32.8	29.5	29.1	31.1
6/13/17	Aerial NDVI	3	28.8	34.1	23.5	27.1	28.4
6/13/17	Aerial NDVI	4	34.4	40.1	17.5	29.1	30.3

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/20/17	Check	1	47.0	45.0	46.0	44.1	45.5
6/20/17	Check	2	46.4	36.1	38.1	32.8	38.4
6/20/17	Check	3	46.0	40.4	36.8	35.1	39.6
6/20/17	Check	4	45.7	48.0	37.1	37.4	42.1
6/20/17	Soil Test	1	44.7	46.7	49.4	44.7	46.4
6/20/17	Soil Test	2	44.4	46.0	44.7	39.1	43.6
6/20/17	Soil Test	3	46.4	51.0	46.2	36.8	45.1
6/20/17	Soil Test	4	45.0	45.7	42.7	38.0	42.9
6/20/17	Split-Soil Test	1	44.7	41.7	42.1	40.4	42.2
6/20/17	Split-Soil Test	2	45.7	45.7	40.4	42.1	43.5
6/20/17	Split-Soil Test	3	49.4	43.7	47.4	49.4	47.5
6/20/17	Split-Soil Test	4	42.0	41.4	50.7	48.0	45.5
6/20/17	Sensor	1	35.8	33.1	34.8	33.4	34.3
6/20/17	Sensor	2	36.4	36.1	38.7	44.1	38.8
6/20/17	Sensor	3	43.7	41.7	44.1	41.1	42.7
6/20/17	Sensor	4	42.1	44.1	36.1	36.1	39.6
6/20/17	Aerial NDVI	1	32.8	35.4	39.2	31.5	34.7
6/20/17	Aerial NDVI	2	41.7	42.1	45.7	39.7	42.3
6/20/17	Aerial NDVI	3	42.7	38.1	39.1	43.4	40.8
6/20/17	Aerial NDVI	4	48.0	40.7	41.7	24.0	38.6

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
6/27/17	Check	1	36.1	38.1	39.1	37.8	37.8
6/27/17	Check	2	40.4	36.1	25.2	32.4	33.5
6/27/17	Check	3	44.1	38.2	35.8	35.4	38.4
6/27/17	Check	4	49.4	46.2	28.5	35.1	39.8
6/27/17	Soil Test	1	42.7	43.1	40.1	39.7	41.4
6/27/17	Soil Test	2	40.0	36.1	30.1	38.4	36.2
6/27/17	Soil Test	3	39.7	36.8	42.4	38.1	39.3
6/27/17	Soil Test	4	37.4	40.1	33.1	39.7	37.6
6/27/17	Split-Soil Test	1	36.4	25.5	38.1	29.8	32.5
6/27/17	Split-Soil Test	2	40.7	43.1	54.3	37.8	44.0
6/27/17	Split-Soil Test	3	50.0	44.4	38.1	30.5	40.8
6/27/17	Split-Soil Test	4	40.1	46.0	36.4	45.7	42.1
6/27/17	Sensor	1	32.8	33.4	21.8	29.1	29.3
6/27/17	Sensor	2	34.1	34.8	32.4	31.5	33.2
6/27/17	Sensor	3	22.1	35.4	37.1	32.8	31.9
6/27/17	Sensor	4	42.1	39.2	36.1	29.1	36.6
6/27/17	Aerial NDVI	1	34.8	28.5	26.5	25.8	28.9
6/27/17	Aerial NDVI	2	39.1	32.4	36.8	35.4	35.9
6/27/17	Aerial NDVI	3	43.1	34.8	35.1	40.7	38.4
6/27/17	Aerial NDVI	4	40.7	28.5	25.8	38.1	33.3

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/4/17	Check	1	45.7	44.4	44.7	43.1	44.5
7/4/17	Check	2	42.4	38.1	35.4	37.4	38.3
7/4/17	Check	3	41.7	38.7	41.4	42.1	41.0
7/4/17	Check	4	45.7	48.7	27.1	29.1	37.7
7/4/17	Soil Test	1	41.4	40.1	46.0	46.4	43.5
7/4/17	Soil Test	2	43.7	45.0	38.1	43.1	42.5
7/4/17	Soil Test	3	40.1	41.4	45.0	41.1	41.9
7/4/17	Soil Test	4	46.4	43.4	47.1	42.4	44.8
7/4/17	Split-Soil Test	1	36.8	32.4	38.7	39.1	36.8
7/4/17	Split-Soil Test	2	36.4	45.7	36.1	34.4	38.2
7/4/17	Split-Soil Test	3	41.7	42.7	53.3	43.4	45.3
7/4/17	Split-Soil Test	4	51.0	43.4	36.4	36.1	41.7
7/4/17	Sensor	1	36.8	37.8	34.8	30.8	35.1
7/4/17	Sensor	2	30.7	30.8	28.1	36.8	31.6
7/4/17	Sensor	3	43.7	35.4	37.4	41.1	39.4
7/4/17	Sensor	4	34.0	48.7	43.1	36.1	40.5
7/4/17	Aerial NDVI	1	33.1	33.1	30.1	32.8	32.3
7/4/17	Aerial NDVI	2	43.4	41.4	44.4	38.4	41.9
7/4/17	Aerial NDVI	3	40.4	35.4	38.4	46.0	40.1
7/4/17	Aerial NDVI	4	42.7	39.7	38.1	39.4	40.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/11/17	Check	1	34.4	31.8	29.8	36.4	33.1
7/11/17	Check	2	29.8	35.1	26.8	29.5	30.3
7/11/17	Check	3	33.1	31.1	31.5	33.8	32.4
7/11/17	Check	4	37.1	37.1	34.8	31.8	35.2
7/11/17	Soil Test	1	29.5	34.2	32.8	29.5	31.5
7/11/17	Soil Test	2	37.1	42.1	39.7	42.1	40.3
7/11/17	Soil Test	3	32.8	36.4	34.4	38.4	35.5
7/11/17	Soil Test	4	40.1	33.4	33.8	34.4	35.4
7/11/17	Split-Soil Test	1	26.8	26.1	21.2	36.1	27.6
7/11/17	Split-Soil Test	2	33.8	34.8	30.5	25.8	31.2
7/11/17	Split-Soil Test	3	37.8	36.4	36.4	38.4	37.3
7/11/17	Split-Soil Test	4	25.8	36.4	30.8	40.1	33.3
7/11/17	Sensor	1	16.5	27.5	24.8	21.5	22.6
7/11/17	Sensor	2	24.8	34.1	30.8	25.2	28.7
7/11/17	Sensor	3	33.4	35.1	29.8	33.1	32.9
7/11/17	Sensor	4	38.7	39.7	34.4	36.4	37.3
7/11/17	Aerial NDVI	1	21.8	23.5	25.2	22.5	23.3
7/11/17	Aerial NDVI	2	31.5	32.1	32.1	33.8	32.4
7/11/17	Aerial NDVI	3	34.4	36.4	27.8	30.5	32.3
7/11/17	Aerial NDVI	4	34.1	32.1	31.5	30.4	32.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/18/17	Check	1	43.4	46.7	44.1	44.1	44.6
7/18/17	Check	2	43.1	43.7	37.1	39.1	40.8
7/18/17	Check	3	45.0	47.4	40.4	39.1	43.0
7/18/17	Check	4	50.0	50.7	44.1	38.4	45.8
7/18/17	Soil Test	1	45.7	49.4	44.4	40.4	45.0
7/18/17	Soil Test	2	44.4	51.7	44.4	54.0	48.6
7/18/17	Soil Test	3	45.7	48.0	43.4	42.7	45.0
7/18/17	Soil Test	4	43.4	44.4	35.4	41.1	41.1
7/18/17	Split-Soil Test	1	44.7	41.7	39.4	36.1	40.5
7/18/17	Split-Soil Test	2	44.4	43.4	37.9	38.1	41.0
7/18/17	Split-Soil Test	3	51.7	48.4	41.4	44.7	46.6
7/18/17	Split-Soil Test	4	41.7	48.0	40.1	37.1	41.7
7/18/17	Sensor	1	37.1	37.1	35.4	28.8	34.6
7/18/17	Sensor	2	39.7	43.4	41.4	36.1	40.2
7/18/17	Sensor	3	43.4	44.4	42.1	38.4	42.1
7/18/17	Sensor	4	39.4	46.4	39.4	39.7	41.2
7/18/17	Aerial NDVI	1	36.1	36.4	32.8	29.1	33.6
7/18/17	Aerial NDVI	2	39.7	42.7	41.4	43.1	41.7
7/18/17	Aerial NDVI	3	39.1	33.1	41.1	35.6	37.2
7/18/17	Aerial NDVI	4	40.4	44.1	42.1	40.1	41.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
7/25/17	Check	1	47.4	46.4	42.0	45.0	45.2
7/25/17	Check	2	48.7	40.7	40.1	38.7	42.1
7/25/17	Check	3	44.4	46.4	36.4	38.7	41.5
7/25/17	Check	4	45.4	45.4	35.8	35.8	40.6
7/25/17	Soil Test	1	48.4	49.7	44.7	41.4	46.1
7/25/17	Soil Test	2	53.7	51.8	51.0	47.0	50.9
7/25/17	Soil Test	3	44.7	40.0	43.4	40.4	42.1
7/25/17	Soil Test	4	44.7	46.4	35.1	38.1	41.1
7/25/17	Split-Soil Test	1	36.1	36.1	34.1	31.1	34.4
7/25/17	Split-Soil Test	2	47.7	46.0	46.7	42.4	45.7
7/25/17	Split-Soil Test	3	46.4	47.7	42.7	42.7	44.9
7/25/17	Split-Soil Test	4	43.4	47.7	40.7	64.9	49.2
7/25/17	Sensor	1	23.8	28.8	18.4	30.1	25.3
7/25/17	Sensor	2	44.1	29.8	38.4	38.4	37.7
7/25/17	Sensor	3	39.7	42.4	42.4	45.4	42.5
7/25/17	Sensor	4	36.1	42.7	42.4	44.7	41.5
7/25/17	Aerial NDVI	1	30.8	27.5	24.2	23.8	26.6
7/25/17	Aerial NDVI	2	45.0	44.7	43.1	40.1	43.2
7/25/17	Aerial NDVI	3	36.8	37.8	43.4	38.4	39.1
7/25/17	Aerial NDVI	4	33.7	44.1	41.4	39.7	39.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/1/17	Check	1	48.0	44.7	43.7	45.0	45.4
8/1/17	Check	2	45.7	40.7	36.4	39.4	40.6
8/1/17	Check	3	44.1	44.7	38.7	42.1	42.4
8/1/17	Check	4	49.0	48.4	39.7	36.1	43.3
8/1/17	Soil Test	1	42.7	44.7	42.1	42.7	43.1
8/1/17	Soil Test	2	50.0	49.0	48.7	46.0	48.4
8/1/17	Soil Test	3	47.4	47.4	46.7	49.0	47.6
8/1/17	Soil Test	4	46.7	38.7	40.1	40.6	41.5
8/1/17	Split-Soil Test	1	36.1	36.1	32.4	33.1	34.4
8/1/17	Split-Soil Test	2	45.0	38.7	40.7	44.4	42.2
8/1/17	Split-Soil Test	3	49.0	48.7	39.1	40.7	44.4
8/1/17	Split-Soil Test	4	49.0	47.4	44.7	40.1	45.3
8/1/17	Sensor	1	33.8	37.1	29.1	33.1	33.3
8/1/17	Sensor	2	42.7	41.7	38.7	38.4	40.4
8/1/17	Sensor	3	43.7	43.4	39.4	49.1	43.9
8/1/17	Sensor	4	43.4	42.1	46.7	41.1	43.3
8/1/17	Aerial NDVI	1	31.1	32.8	27.1	27.8	29.7
8/1/17	Aerial NDVI	2	44.7	39.1	40.7	43.4	42.0
8/1/17	Aerial NDVI	3	38.4	36.8	40.7	40.7	39.2
8/1/17	Aerial NDVI	4	46.0	43.4	37.4	43.4	42.6

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/8/17	Check	1	45.3	39.7	40.5	49.4	43.7
8/8/17	Check	2	36.8	46.0	43.4	39.7	41.5
8/8/17	Check	3	43.4	43.7	40.4	37.1	41.2
8/8/17	Check	4	47.4	42.4	39.7	47.0	44.1
8/8/17	Soil Test	1	43.7	46.1	45.4	44.1	44.8
8/8/17	Soil Test	2	49.4	49.7	46.7	46.4	48.1
8/8/17	Soil Test	3	46.7	46.7	48.7	43.4	46.4
8/8/17	Soil Test	4	40.1	44.4	40.7	39.4	41.2
8/8/17	Split-Soil Test	1	35.4	38.7	36.1	28.5	34.7
8/8/17	Split-Soil Test	2	42.4	34.1	38.1	36.8	37.9
8/8/17	Split-Soil Test	3	41.4	45.7	40.4	37.4	41.2
8/8/17	Split-Soil Test	4	46.1	41.1	45.7	44.7	44.4
8/8/17	Sensor	1	30.1	38.7	32.1	25.2	31.5
8/8/17	Sensor	2	38.7	41.1	39.1	36.1	38.8
8/8/17	Sensor	3	42.4	42.4	36.8	39.1	40.2
8/8/17	Sensor	4	44.4	44.4	41.4	39.1	42.3
8/8/17	Aerial NDVI	1	29.8	32.8	34.1	35.1	33.0
8/8/17	Aerial NDVI	2	36.4	43.1	39.4	38.7	39.4
8/8/17	Aerial NDVI	3	38.1	32.4	30.4	36.4	34.3
8/8/17	Aerial NDVI	4	43.7	44.4	40.1	40.1	42.1

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
8/29/17	Check	1	42.1	37.8	34.4	38.1	38.1
8/29/17	Check	2	35.8	32.8	40.1	39.4	37.0
8/29/17	Check	3	42.1	41.7	37.8	39.1	40.2
8/29/17	Check	4	45.0	45.4	41.4	39.7	42.9
8/29/17	Soil Test	1	38.7	36.8	37.1	37.1	37.4
8/29/17	Soil Test	2	44.1	41.4	39.1	42.7	41.8
8/29/17	Soil Test	3	45.0	41.1	44.1	46.4	44.2
8/29/17	Soil Test	4	40.1	41.7	38.7	42.1	40.7
8/29/17	Split-Soil Test	1	33.4	29.8	29.1	29.5	30.5
8/29/17	Split-Soil Test	2	39.1	39.7	36.1	36.1	37.8
8/29/17	Split-Soil Test	3	45.4	46.0	42.4	39.1	43.2
8/29/17	Split-Soil Test	4	49.7	50.0	42.4	42.7	46.2
8/29/17	Sensor	1	30.5	29.8	25.2	28.5	28.5
8/29/17	Sensor	2	38.7	38.4	34.8	37.4	37.3
8/29/17	Sensor	3	37.8	40.4	41.4	40.7	40.1
8/29/17	Sensor	4	40.7	41.7	41.1	37.8	40.3
8/29/17	Aerial NDVI	1	30.5	28.5	25.8	26.8	27.9
8/29/17	Aerial NDVI	2	38.1	38.1	38.7	38.4	38.3
8/29/17	Aerial NDVI	3	41.4	36.4	35.1	38.4	37.8
8/29/17	Aerial NDVI	4	46.4	36.4	41.7	42.1	41.7

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/5/17	Check	1	32.8	35.8	32.1	35.8	34.1
9/5/17	Check	2	35.4	22.5	36.4	26.1	30.1
9/5/17	Check	3	36.4	33.1	33.4	26.5	32.4
9/5/17	Check	4	39.1	38.1	23.8	31.8	33.2
9/5/17	Soil Test	1	33.4	30.5	33.1	31.5	32.1
9/5/17	Soil Test	2	42.4	40.7	28.1	37.8	37.3
9/5/17	Soil Test	3	31.1	35.8	33.4	36.4	34.2
9/5/17	Soil Test	4	35.4	32.1	34.4	34.1	34.0
9/5/17	Split-Soil Test	1	25.8	19.5	19.2	24.2	22.2
9/5/17	Split-Soil Test	2	33.8	31.8	31.1	29.1	31.5
9/5/17	Split-Soil Test	3	39.1	32.6	29.8	23.5	31.3
9/5/17	Split-Soil Test	4	42.7	40.7	35.1	32.1	37.7
9/5/17	Sensor	1	22.5	23.8	21.2	27.5	23.8
9/5/17	Sensor	2	33.4	32.4	25.2	28.5	29.9
9/5/17	Sensor	3	32.8	33.8	23.8	29.5	30.0
9/5/17	Sensor	4	37.1	36.1	28.1	30.5	33.0
9/5/17	Aerial NDVI	1	24.5	23.8	20.5	22.8	22.9
9/5/17	Aerial NDVI	2	29.1	30.5	23.8	29.5	28.2
9/5/17	Aerial NDVI	3	31.8	33.4	29.8	32.1	31.8
9/5/17	Aerial NDVI	4	30.1	31.8	22.8	27.1	28.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/12/17	Check	1	32.4	36.8	26.8	27.8	31.0
9/12/17	Check	2	18.5	25.8	23.8	28.5	24.2
9/12/17	Check	3	24.8	36.8	25.5	29.8	29.2
9/12/17	Check	4	32.8	35.4	25.2	25.5	29.7
9/12/17	Soil Test	1	29.5	28.8	27.8	22.8	27.2
9/12/17	Soil Test	2	41.1	31.8	37.9	23.5	33.6
9/12/17	Soil Test	3	35.4	34.8	30.5	34.1	33.7
9/12/17	Soil Test	4	34.8	21.5	33.4	23.8	28.4
9/12/17	Split-Soil Test	1	16.2	24.8	19.8	16.2	19.3
9/12/17	Split-Soil Test	2	30.8	23.8	20.0	29.1	25.9
9/12/17	Split-Soil Test	3	30.5	34.4	25.8	23.5	28.6
9/12/17	Split-Soil Test	4	38.1	37.4	21.5	16.2	28.3
9/12/17	Sensor	1	21.8	25.8	20.5	18.9	21.8
9/12/17	Sensor	2	33.8	26.8	27.8	26.5	28.7
9/12/17	Sensor	3	26.8	29.5	33.4	30.1	30.0
9/12/17	Sensor	4	24.5	33.1	25.5	29.5	28.2
9/12/17	Aerial NDVI	1	19.2	17.5	19.8	22.2	19.7
9/12/17	Aerial NDVI	2	33.4	28.8	31.1	24.4	29.4
9/12/17	Aerial NDVI	3	25.2	30.5	26.9	27.1	27.4
9/12/17	Aerial NDVI	4	28.8	33.4	23.2	26.5	28.0

Date	Treatment	Block	% Volumetric Water Content				
			1	2	3	4	Average
9/23/17	Check	1	39.7	34.1	37.1	37.4	37.1
9/23/17	Check	2	38.7	32.4	27.1	28.5	31.7
9/23/17	Check	3	34.1	38.1	27.1	30.8	32.5
9/23/17	Check	4	35.1	39.1	27.5	32.8	33.6
9/23/17	Soil Test	1	36.4	39.4	40.4	35.8	38.0
9/23/17	Soil Test	2	41.4	27.4	30.1	26.1	31.3
9/23/17	Soil Test	3	36.4	39.4	37.8	34.4	37.0
9/23/17	Soil Test	4	34.1	36.8	29.8	30.1	32.7
9/23/17	Split-Soil Test	1	33.4	27.1	27.5	24.8	28.2
9/23/17	Split-Soil Test	2	40.1	39.4	40.4	37.8	39.4
9/23/17	Split-Soil Test	3	40.7	44.7	41.4	34.1	40.2
9/23/17	Split-Soil Test	4	45.4	47.4	49.4	42.4	46.2
9/23/17	Sensor	1	28.1	28.5	34.1	27.5	29.6
9/23/17	Sensor	2	32.8	26.5	36.1	29.8	31.3
9/23/17	Sensor	3	34.8	37.8	29.8	34.1	34.1
9/23/17	Sensor	4	36.8	40.1	28.5	27.1	33.1
9/23/17	Aerial NDVI	1	27.5	29.8	28.8	25.5	27.9
9/23/17	Aerial NDVI	2	37.1	34.1	29.5	25.5	31.6
9/23/17	Aerial NDVI	3	30.8	33.8	32.8	30.1	31.9
9/23/17	Aerial NDVI	4	35.8	32.8	31.1	28.8	32.1

Appendix C - Soil Nitrogen

Materials and Methods

Soil nitrogen samples were collected at the time of each gas-sampling event. Eight 15 cm cores were collected from inter-rows three and four, four cores from each inter-row, and were composited. A Collect-N-GO Soil Sample Collection Power Kit (Collect-N-GO) was used to collect soil cores. Samples were placed in a convection oven at 42˚C until sample mass was static. Dry samples were ground using a screw-type auger and passed through a 2-mm screen. After samples were prepared they were sent to the Kansas State University Soil Testing Laboratory for soil nitrate and ammonium analysis. 20 mL of 1 M KCl was added to 2 g of soil and oscillated for 30 min. Soil nitrate was analyzed using the method described by Gelderman and Beegle (1998). Indophenol colorimetric reaction described by Keeney and Nelson (1982) was used to quantify ammonium.

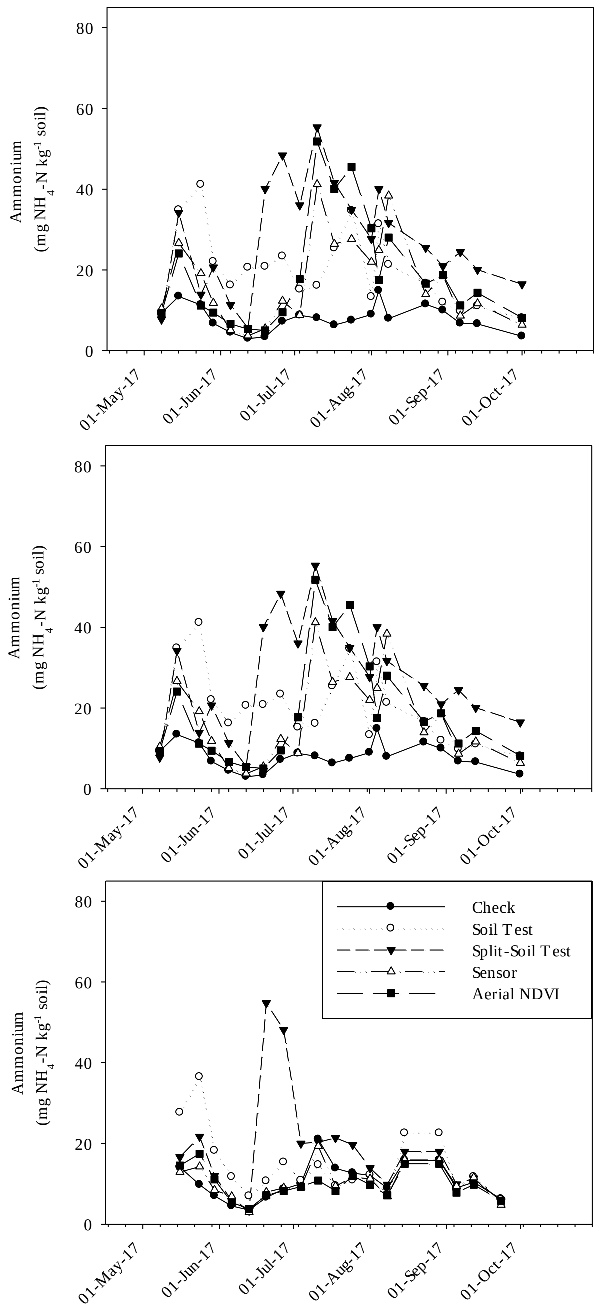

Figure C.1 Soil ammonium for Manhattan 2016 (a), Manhattan 2017 (b), and Topeka 2017 (c).

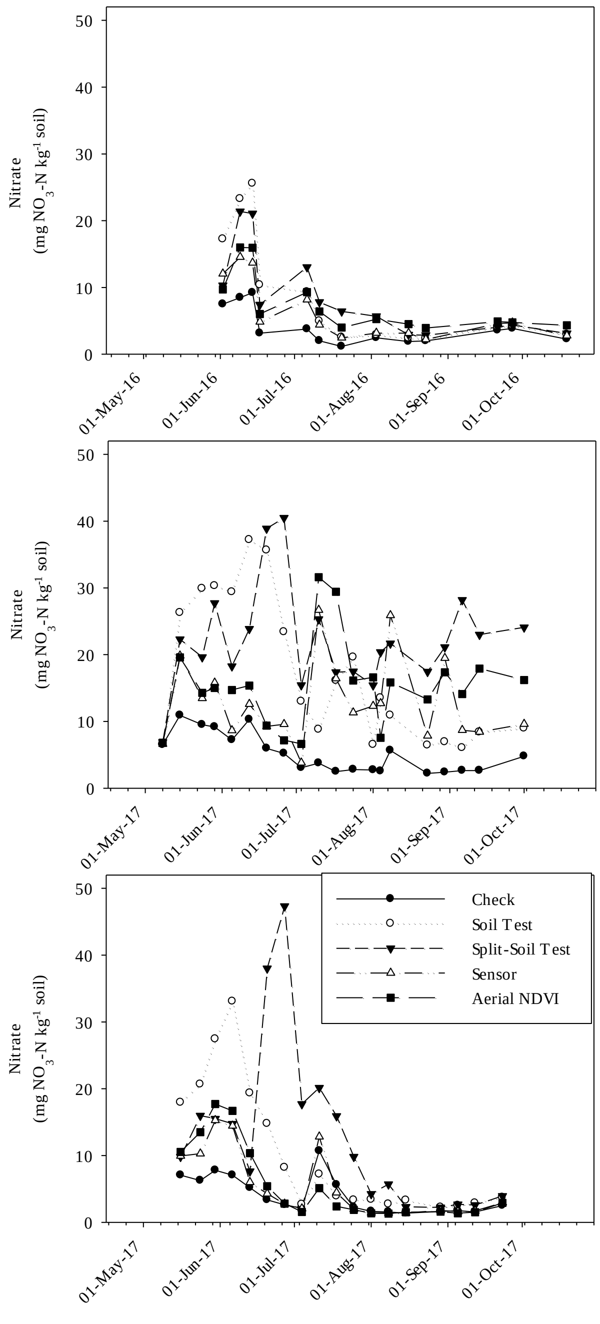

Figure C.2 Soil nitrate for Manhattan 2016 (a), Manhattan 2017 (b), and Topeka 2017 (c).

Bibliography

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Keeney, D.R. and D.W. Nelson. 1982. Nitrogen - inorganic forms. p. 643-698. In A.L. Page (ed.) Methods of soil analysis: Part 2. ASA, SSSA, Madison, WI.

Appendix D - Nitrous Oxide SAS Code

Yield

```
PROC MIXED DATA=Appendix;
CLASS TREAT BLOCK;
MODEL YIELD=TREAT/residual DDFM=KR;
RANDOM BLOCK;
lsmeans TREAT/pdiff;
ods output diffs=diffs;
ods output diffs=ppp lsmeans=mmm;
ods listing exclude diffs lsmeans;
run;
data lsd;
set diffs;
lsd = stderr*tinv(0.975,df);
run;
proc print data=lsd;
run;
%include 'C:\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=yes);
QUIT;
```

Cumulative Nitrous Oxide

```
PROC MIXED DATA=Appendix
CLASS TREAT BLOCK;
MODEL N2O=TREAT/residual DDFM=KR;
RANDOM BLOCK;
lsmeans TREAT/PDIFF;
ods output diffs=diffs;
ods output diffs=ppp lsmeans=mmm;
ods listing exclude diffs lsmeans;
run;
data lsd;
set diffs;
lsd = stderr*tinv(0.975,df);
run;
proc print data=lsd;
run;
%include 'C:\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=yes);
QUIT;
```

Yield-scaled Nitrous Oxide Emissions

```
PROC MIXED DATA=Appendix;
CLASS TREAT BLOCK;
MODEL YSNE=TREAT/residual DDFM=KR;
RANDOM BLOCK;
lsmeans TREAT/pdiff;
ods output diffs=diffs;
ods output diffs=ppp lsmeans=mmm;
ods listing exclude diffs lsmeans;
run;
data lsd;
set diffs;
lsd = stderr*tinv(0.975,df);
run;
proc print data=lsd;
run;
%include 'C:\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=yes);
QUIT;
```

Fertilizer Induced Emissions

```
PROC MIXED DATA=Appendix;
CLASS TREAT BLOCK;
MODEL FIE=TREAT/residual DDFM=KR;
RANDOM BLOCK;
lsmeans TREAT/pdiff;
ods output diffs=diffs;
ods output diffs=ppp lsmeans=mmm;
ods listing exclude diffs lsmeans;
run;
data lsd;
set diffs;
lsd = stderr*tinv(0.975,df);
run;
proc print data=lsd;
run;
%include 'C:\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=yes);
QUIT;
```

Emissions Factor

```
PROC MIXED DATA=Appendix;
CLASS TREAT BLOCK;
MODEL EF=TREAT/residual DDFM=KR;
RANDOM BLOCK;
lsmeans TREAT/pdiff;
ods output diffs=diffs;
ods output diffs=ppp lsmeans=mmm;
ods listing exclude diffs lsmeans;
run;
data lsd;
set diffs;
lsd = stderr*tinv(0.975,df);
run;
proc print data=lsd;
run;
%include 'C:\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=.05,sort=yes);
QUIT;
```