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LATERAL SPACING OF SUBSURFACE POULTRY LITTER BANDS: EFFECT ON GASEOUS NITROGEN EMISSIONS, NUTRIENT UPTAKE, AND MAIZE YIELD

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LATERAL SPACING OF SUBSURFACE POULTRY LITTER BANDS: EFFECT ON GASEOUS NITROGEN EMISSIONS, NUTRIENT UPTAKE, AND MAIZE YIELD

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Agriculture, Food and Environment
at the University of Kentucky

By

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ABSTRACT OF DISSERTATION

LATERAL SPACING OF SUBSURFACE POULTRY LITTER BANDS: EFFECT ON GASEOUS NITROGEN EMISSIONS, NUTRIENT UPTAKE AND MAIZE YIELD

Poultry litter (PL) is traditionally applied to no-till maize (*Zea mays* L.) cropping systems by surface broadcast. Poultry litter is nutrient dense, and it has been repeatedly shown that surface applied PL nitrogen (N) is vulnerable to losses to the atmosphere and nearby water systems. An application method was developed by USDA-Agricultural Research Service scientists for banding poultry litter (PL) below the soil surface with minimal soil disturbance to reduce ammonia (NH_3) volatilization and surface run-off. It is well documented that subsurface applied poultry litter (PL) reduces N losses by ammonia (NH_3) volatilization; however, the effect of this application method on N_2O emissions and crop yields have been mixed. Nitrogen fertilization of agricultural soil stimulates nitrous oxide (N_2O) production, a potent greenhouse gas, and accounts for over 75% of the anthropogenic N_2O emissions globally. Best management practices for land application of animal manures as a source of N don't primarily address the effect they have on N_2O emissions. A two-year field experiment was initiated May 2014 on a Crider silt loam to determine if subsurface applying PL in multiple bands between maize (*Zea mays* L.) rows influenced N_2O emissions, NH_3 volatilization, nutrient use, and maize yield. Treatments consisted of an untreated control (UTC), urea ammonium nitrate (UAN, 32% N) surface banded (Fert), PL surface broadcast (PLBr), and three subsurface banded PL treatments. The subsurface PL treatments were 1 (PLSub1), 2 (PLSub2), and 3 (PLSub3) lateral bands in the inter-maize row area. Treatments receiving N amendments were added at 180 kg total N ha^{-1} each spring prior to maize planting. Nitrous oxide emission varied each growing season and N_2O pulses coincided with rainfall events larger than 1-cm following treatment application. Subsurface banding PL had significantly lower ($P < 0.1$) cumulative N_2O emissions than PLBr in 2014 and 2015 in at least some treatments. Surface broadcasting PL had greater NH_3 volatilization than all PLSub treatments, which agrees with other studies. There were no differences between PLSub treatments in 2014 and 2015 for cumulative N_2O emissions and NH_3 volatilization. Nitrogen concentration in V4 maize aboveground dry matter was significantly higher in PLSub1 than PLSub2. Aboveground biomass yields for all PLSub treatments were greater than PLBr and similar to Fert. Subsurface PL application in 1 and 2 bands resulted in maize grain yields similar to Fert and significantly greater than PLBr and UTC when averaged across years. Few significant differences were observed in post-harvest soil sample nutrient concentrations between PLSub treatments. These results suggested that subsurface banding PL can reduce N_2O

emissions, conserve N, and increase no-till maize yields compared to the traditional method of surface broadcasting PL. Increasing the frequency of subsurface PL bands between maize rows did not clearly affect N_2O emissions, nutrient conservation, or nutrient utilization by maize across the growing season.

KEYWORDS: nitrous oxide, ammonia, greenhouse gas, fertilizer, manure

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CHAPTER 1. GENERAL INTRODUCTION

1.1 Poultry Litter Production

Poultry has been the top meat commodity in the world for the past three decades, surpassing pork and beef. The United States is the top producer of broilers (*Gallus gallus domesticus*) globally and according to the 2017 Census of Agriculture (NASS, 2017) there were nearly 9 billion head of broilers sold. Kentucky was ranked eighth nationally in total broiler production in 2021 of states that disclosed information to the National Agricultural Statistics Service (NASS, 2022b). The poultry industry in Kentucky was non-existent in 1988 (Rasnake, 1996) but currently it is the second highest commodity in terms of state revenue with nearly 300 million head sold (NASS, 2022a).

This large increase in broiler production simultaneously generated tremendous amounts of the waste by-product poultry litter (PL). Poultry litter is a combination of poultry manure, C-based bedding materials, feathers, and wasted feed. Bedding materials include (but are not limited to) wood shavings, sawdust, rice hulls, peanut hulls, or cereal straw used to absorb the liquid portion of the poultry manure. According to the Kentucky Poultry Federation (2023) there are 3200 poultry houses in 49 counties across the state. Assuming 190 Mg of PL per house (Jordan Shockley, personal communication, 2023), they would generate 608,000 Mg of PL annually. Moore et al. (1995) reported that in 1990 greater than 90% of poultry litter was land applied as a crop nutrient source. According the 2017 Census of Agriculture (NASS, 2017) the top broiler producing counties in Kentucky were Graves, McLean, Hickman, Webster, and Ohio, which are all counties that have a prevalent amount of land devoted to row-crops suitable to utilize PL as a nutrient source.

When the broiler industry started in Kentucky it was common practice for producers to perform total cleanouts of the PL in the houses every 8-10 flocks to limit moisture content of the spent litter and improve broiler health. It is now common practice for producers to "decake" or remove the wet, fresh litter from each flock that accumulates in the top 10-cm of the bedding material (Sistani et al., 2003). This not only resolves the issue associated with moisture accumulation in the PL but also allows the producer to prolong the lifespan of the bedding material up to 5 years or more. The "decaking" process generally removes 18-23 Mg of PL from each house following the flock harvest (Fitzgerald, 2019).

1.2 Poultry Litter Composition

Poultry litter is similar to other manure sources in that the moisture content, pH, and nutrient composition fluctuate due to feed components and ratios, number of flocks, flock density, type of bedding material, litter amendments, in-house environment conditions, and manure handling (Edwards and Daniel, 1992). The University of Kentucky recommends sampling PL for nutrient analysis as close to the application date as possible to get the most accurate assessment of nutrients applied (Rasnake, 1996). Poultry litter is considered one of the most valued livestock manures due to the relative low water content, high macronutrient content (N, P and K), secondary nutrients (Ca, Mg and S) and additional trace nutrients (Cu, Zn and Mo) required for optimal plant growth (Bolan et al., 2010).

The nutrients in PL are inorganic and organic. Ammoniacal N is the main inorganic N form in PL followed by lesser amounts of nitrate, both which are readily available for plant use. A review on poultry waste disposal by Edwards and Daniel (1992) reported mean concentrations of 2.6, 0.2, and 41.0-g kg^{-1} for ammoniacal N, nitrate-N (NO_3^--N), and organic N in PL. The organic N in PL can be mineralized into complex and labile organic N compounds. Feathers, wasted feed, and bedding materials constitute the complex forms of organic N while uric acid and urea largely compose the labile organic N fraction. Following fresh deposition of excreta from broilers, the uric acid is quickly hydrolyzed by uricase enzyme to urea and then urea is hydrolyzed by urease enzyme to ammoniacal N (Bolan et al., 2010). Additional organic N forms in PL include proteins, amino acids, and amino sugars. Increased addition of protein and amino acid supplements to poultry feed has caused amino N concentration in PL to nearly double what it was several decades ago (Ashworth et al., 2020a).

The ammoniacal N can either be in the form of NH_4^+ or NH_3 depending on the moisture content and pH of the PL. The normally neutral or alkaline pH of PL combined with high moisture content near water lines can enhance microbial and enzymatic breakdown of uric acid and urea, increasing the NH_3 fraction and subsequent emission from the PL. More than 50% of the N in PL can be lost to NH_3 volatilization due to microbial activity (Brinson et al., 1994; Moore et al., 1996). Poultry health can be negatively affected when NH_3 concentrations in the ambient air inside the poultry houses exceed 25 ppm, which can lead to decreased growth rates and increased mortality rates.

Producers can apply several chemical amendments to reduce NH_3 concentrations in the poultry house that either slow uric acid decomposition by inhibiting microbial growth or neutralize the NH_3 (Moore et al., 1996). Applying aluminum sulfate and sodium bisulfate as acidifying agents are common industry practices to lower the pH of the PL and reduce the NH_3/NH_4^+-N ratio. Meisinger and Jokela (2000) noted that reducing PL pH below 7 will favor the speciation of NH_4^+ over NH_3 , resulting in NH_3 concentrations 1% that of the total ammoniacal N.

The concentration and availability of N in PL is affected by many factors including poultry flock management, “de-caking” and total clean out cycles, manure handling and storage, application timing, application method, and soil N mineralization rates following application. Nitrogen mineralization in the soil is a combination of microbial and enzymatic driven processes that change organic N to plant available inorganic N. The two main processes that drive N mineralization are aminization followed by ammonification. Aminization converts complex organic N compounds to simple organic N forms such as nucleic acids and amino N compounds. These simple organic N forms (including uric acid and urea) are then converted to ammoniacal N by ammonification. The microbial activity governing N mineralization processes are influenced by soil temperature, moisture, oxygen content, and pH (Edwards and Daniel, 1992; Fitzgerald, 2019; Lin et al., 2018).

The University of Kentucky recommends PL spring application rates based on assuming 45 to 60% of the N will be available to the maize crop dependent on when the PL is incorporated into the soil (Rasnake et al., 2000). Edwards and Daniel (1992) reported mean concentrations of 14.3 g total P kg^{-1} PL and 20.7 g K kg^{-1} PL in a review focused on on-farm poultry waste disposal. Research suggests that greater than 90% of the P and K in PL is readily available for plant use during the growing season (Sharpley and Moyer, 2000) with lability comparable to synthetic fertilizers (Pagliari and Laboski, 2014). The University of Kentucky suggests that 80% of the phosphate and 100% of the potash in manures will be available to the crop during the first growing season (Rasnake et al., 2000). The K concentration in PL is 100% readily available because K is not a constituent in organic compounds (Ashworth et al., 2020a).

Past studies note that two-thirds of the total P in PL is organic and the remainder is inorganic P (Bolan et al., 2010; Edwards and Daniel, 1992; Sharpley et al., 2004). Phytic acid salts are the main organic P compounds in PL while the inorganic P forms are dibasic calcium phosphate, calcium phosphate, and weakly bound water soluble phosphate (Bolan et al., 2010). Nearly two-thirds of organic P consumed by broilers is deposited in the manure because the bird's digestive system lacks the phytase enzyme required to mineralize the phytate form of P found in maize and soybeans (*Glycine max* L.) (Patterson et al., 2005). Much of the P in the poultry diet is from the addition of inorganic P supplements (defluorinated, monocalcium, and dicalcium phosphate) and enzymes that assist the birds in improving nutrient recovery from the feed (Sharpley et al., 2007).

1.3 Poultry Litter as a Maize Nutrient Source

Maize for grain production was the top agricultural commodity for total cash receipts in 2021 for Kentucky with a revenue over $1.2 billion, along with record average grain yields of 12 Mg ha^{-1} (NASS, 2022a). In general, most Kentucky soils depend on supplemental N fertilization to optimize maize grain yields. Poultry litter has increasingly been used as a nutrient source for maize production in areas where the poultry industry is concentrated and poultry litter production in Kentucky is generally concentrated where maize cropping prevails. McLean, Hickman, and Webster counties are in the top five and top ten Kentucky counties in terms of broiler and maize grain production, respectively (NASS, 2022a).

Poultry litter improves soil fertility by adding essential plant nutrients (Sistani et al., 2008), but has supplementary benefits for soil organic C accumulation (Adeli et al., 2011; Ashworth et al., 2014) and increasing pH of acidic soils (Adeli et al., 2011; Rasnake, 1996; Shockley et al., 2016; Tewolde et al., 2011). Even though average nutrient concentrations for PL are available from multiple sources, it is a best management practice to get a nutrient analysis completed as close to application date as possible (Rasnake, 1996). Poultry litter differs from commercial fertilizers in that multiple elements can be in organic and inorganic forms, which can make it difficult to predict the quantity that will become available to the crop during the growing season. Additionally, the nutrient concentration of PL can fluctuate even from the same poultry farm due to the number of flocks on the PL, being "de-cake" or total cleanout PL, season PL was harvested (moisture), and storage method.

1.3.1 Poultry Litter Land Application

Poultry litter application to agricultural soils serves two purposes: alleviating the accumulation of the poultry waste by-product and supplying required plant nutrients for optimal crop growth. Historically, PL was surface broadcast onto pastures and forages in the general vicinity where the PL was generated. Repeated applications on these lands caused P accumulation in excess of that required for optimal crop growth (Sharpley et al., 1993; Sims et al., 1998). This is because PL has a fertilizer equivalency of approximately 3.0% N, 1.3% P, and 2.5% K and application rates based on N requirements of the crop generally result in applied P exceeding crop P removal. Over the past few decades row crop producers have discovered the benefits of utilizing PL as nutrient source, providing additional agricultural land for dispersing PL nutrients.

A meta-analysis by Lin et al. (2018) investigated the influence of PL on crop productivity from 90 past studies and reported that PL had significantly greater crop yields in no-till systems than inorganic fertilizers. A no-till field study by Sistani et al. (2014) found there were no significant differences in maize grain yields between surface applied PL and that of traditional and enhanced-efficiency inorganic fertilizer sources. Warren et al. (2006) reported reduced maize grain yields from PL surface broadcast followed by tillage incorporation compared to inorganic fertilizer at the same plant available N rate. The decrease in grain yields was attributed to overestimating N availability from the PL during the growing season.

Lin et al. (2018) also tested the residual effects of PL on crop productivity for up to four years without any fertility for 37 of the 866 total observations in the meta-analysis. The residual carryover of PL nutrients on subsequent years without additional fertilizer slightly improved crop yields compared to the residual effect of inorganic fertilizers. The greatest effect of the residual fertility was in the first year after application. Tewolde et al. (2013a) found that PL had significantly greater maize grain yields than inorganic fertilizer in the second and third year of application. The increased yields in the final two years were attributed to residual nutrients from the first year of application becoming plant available in the following growing seasons.

This residual effect due to the slower release of nutrients from PL mineralization could provide a wider application window prior to crop establishment. Regardless of location, a meta-analysis by Lin et al. (2018) concluded that PL applied greater than 30-d prior to crop establishment resulted in significantly higher crop yields compared to that of inorganic fertilizer. Jn-Baptiste et al. (2012) and Ruiz Diaz and Sawyer (2008) investigated application timing of tillage incorporated PL in maize field studies in Kentucky and Iowa, respectively, and found there were no differences in grain yield among PL treatments that were applied in fall or spring. Both studies noted that PL application in fall may be an option for producers if soil temperatures remain below 10°C, which could reduce mineralization and nitrification processes until warmer weather in spring. However, fall PL application may not be an economical option for producers in the southern United States where most of the poultry industry is concentrated and soil temperatures do not remain below 10°C. Tewolde et al. (2013a) found that maize grain yields in Mississippi were reduced by 12.8% when tillage incorporated PL was applied in fall compared to spring.

Application placement of PL can influence plant N availability. It is a basic aspect of the “4R” concept of nutrient stewardship, which includes using the right rate, right source, right timing, and right placement of nutrient amendments. The University of Kentucky recommends that PL be incorporated into the soil by tillage or precipitation event greater than 1.3-cm within 2-d following PL surface application to reduce N loss from NH_3 volatilization (Rasnake et al., 2000). In a tilled cropping system, incorporating PL to a 5-cm following surface application by using a disk reduced NH_3 emissions by 67% compared to unincorporated surface broadcast PL (Pote and Meisinger , 2014). These data agree with a study by Schilke-Gartley and Sims (1993) that indicated 31% of the total N from surface applied PL was lost through NH_3 volatilization; however, losses were greatly reduced when PL was incorporated into the soil by tillage. Ammonia-N incorporated below the soil surface, is quickly hydrolyzed in the soil solution to form NH_4^+, which reduces volatility, but which is subject to nitrification if conditions are favorable.

Poultry litter is traditionally surface broadcast in no-till cropping systems, which can reduce its effectiveness as a nutrient source due to the potential for nutrient loss though volatilization and surface runoff (Kleinman and Sharpley, 2003; Pote and Meisinger, 2014; Pote et al., 2011; Sharpley, 1997; Sistani et al., 2009). The nutrient value of the PL decreases when N is lost due to NH_3 volatilization, which can create an economic burden on the producer if the loss affects crop yields. Past studies show NH_3 volatilization can generally account for up to 30% N loss of the TN applied from PL surface application (Brinson et al., 1994; Cabrera and Chiang, 1994; Cabrera et al., 1994; Pote and Meisinger, 2014; Sharpe et al., 2004).

Environmental concerns associated with NH_3 volatilization to the atmosphere include contributing to acid rain (Sharpe et al., 2004), eutrophication from deposition of N into surface water bodies (Hutchinson and Viets, 1969), and aerosols when ammonia reacts with nitrates and sulfates in the atmosphere causing human respiratory issues and increasing global radiation (Behera et al., 2013). Additionally, NH_3 volatilization can result in indirect N_2O emissions by subsequent atmospheric deposition of NH_3 to terrestrial and aquatic ecosystems (IPCC, 2006).

Ammonia volatilization losses are greatly reduced for surface applied PL when incorporated with tillage or as little as 1.3-cm of rainfall (Rasnake et al., 2000). However, the PL exposed on the soil surface could result in nutrient loss in surface run-off during intense rainfall events before being incorporated below the soil surface. A natural rainfall run-off study by Heathman et al. (1994) found that mean total N and total P concentrations in surface run-off from bermudagrass (*Cynodon dactylon*) plots receiving PL were 3 and 6 times greater than that of the control plots, respectively. A simulated rainfall study by Sistani et al. (2009) noted that total P and NO_3^--N in the first surface run-off event from surface applied PL was significantly higher than inorganic fertilizer. The authors added that increasing the time between PL application and the first run-off event reduced nutrient losses; however, losses were still greater than control plots.

Agricultural lands are responsible for water quality issues for an estimated 70% of surface bodies of water in the United States due to non-point source run-off of P (U.S. EPA, 1994). Phosphorus and nitrate are required elements in facilitating eutrophication, which is a natural process in aquatic ecosystems (Schindler, 1977). Enhanced eutrophication by nutrient enrichment in water bodies can cause harmful blooms of algal growth that consume dissolved oxygen in the water, can cause fish kills, and alter the biodiversity of aquatic life.

The ratio of N:P in PL is generally less than that of crop requirements, which often leads to a surplus of P in the soil when application rates target N needs (Moore Jr, 1998). The loss of N and P from agricultural lands fertilized with PL in surface run-off can be influenced by many factors including: management of the soil surface, application method, timing, and rate, and intensity of precipitation (Edwards and Daniel, 1992; McLeod and Hegg, 1984; Robinson and Sharpley, 1995). The University of Kentucky suggests that producers develop nutrient management plans that base organic fertilizer application rates on the amount of P removed for the targeted crop during the growing season (Higgins et al., 2016).

1.3.2 Poultry Litter Subsurface Banding Application

To reduce environmental issues associated with surface broadcast PL in no-till, researchers developed an experimental implement to subsurface apply PL in bands beneath the soil with minimal surface disturbance (Way et al., 2013). The implement uses a distributor and conveyor system to deliver PL from a large hopper to adjustable row trenchers that place PL into narrow bands below the soil surface while simultaneously covering the band with nearly 6-cm of soil. The subsurface PL implement is currently still in the development stage and isn't available commercially for poultry producers. A recent thesis by Stults (2021) investigated the economic feasibility of a producer integrating subsurface PL banding implement into their operation. The author noted the greatest obstacle is the initial purchase price of the implement. The producer would need to subsurface band PL on more than 165 ha to gain a lower cost per hectare than commercial fertilizer application. For the subsurface banded technology to be more cost-effective than traditional surface broadcast equipment for PL, the producer would need to apply PL to over 900 ha.

The PL subsurface banding implement is effective in reducing ammonia volatilization and nutrient losses in runoff. Ammonia volatilization losses decreased by 95% in no-till maize when PL was subsurface banded compared to surface application and was statistically not different than untreated control plots (Pote et al., 2011). Similarly, NH_3 volatilization was mitigated by an average of 88% when PL was subsurface banded rather than conventional surface broadcast in a conservation tillage maize system (Pote and Meisinger, 2014). Numerous rainfall simulation studies have reported up to 90% reduction in P and other nutrients when PL is subsurface banded rather than surface broadcast in no-till maize, cotton (*Gossypium hirsutum* L.) and permanent pastures (Adeli et al., 2013; Sistani et al., 2009; Watts and Way, 2019; Watts et al., 2011; Watts et al., 2015b).

Management strategies that minimize potential environmental losses should also be agronomically favorable for producers to integrate in their operation. Subsurface banding of PL conserves applied N and improves crop yields. Tewolde et al. (2022) compared the fertilizer value of PL in maize applied by subsurface band and surface broadcast. Subsurface banding PL had >40% plant available N compared to <37% for surface broadcast PL. Maize grain yields were increased by 45% on average when PL was subsurface banded rather than surface broadcast (Ashworth and Nieman , 2022)). Maize silage yields were improved by 30% in the same study. Cotton lint yield increased from 984 kg ha^{-1} for PL surface broadcast to 1052 kg ha^{-1} for PL subsurface banded at an application rate of 6.7 Mg ha^{-1} (Tewolde et al. , 2009)). The authors suggested PL surface broadcast application rates can be reduced by 30% when subsurface banded to produce equivalent cotton lint yields. Tewolde et al. (2018a) compared 30-cm and 102-cm subsurface PL band spacing in cotton and found that the spacing of subsurface PL bands did not consistently affect lint yields. The authors did note that after three years of PL application, the subsurface PL in a single "thick" band (102-cm spacing) had significantly higher average lint yields for the subsequent two years without N fertilization than multiple subsurface PL "thin" bands (30-cm spacing). The authors explained this increase in lint yield was likely due to greater conservation of nutrients and residual effects when PL was concentrated in one single subsurface band between cotton rows.

The N conserved from mitigating NH_3 losses by subsurface banding PL can increase N_2O emissions during the growing season. Nitrous oxide is a greenhouse gas that has 265 times the global warming potential of carbon dioxide (CO_2) over a 100-yr time frame, can persist in the atmosphere for 114 yr, and causes ozone layer depletion in the stratosphere. Agricultural soils account for 74% of the anthropogenic N_2O emissions and 4.5% of total greenhouse gas emissions in the United States (U.S. EPA, 2023). Nitrous oxide is produced naturally in the soil through the biochemical processes of nitrification and denitrification (Hatfield, 2016; Hutchinson and Davidson, 1993; Mosier et al., 2005). Emission of N_2O can occur under a wide range of soil conditions due to nitrification being an aerobic microbial process and denitrification occurring in anaerobic environments. Both soil processes can be influenced by many factors, including soil water content, inorganic N concentrations, available C, oxygen content, temperature, and pH.

Land application of PL enriches the atmosphere with N_2O (Davis et al., 2019; Nyakatawa et al., 2011; Sistani et al., 2011; Sistani et al., 2019; Smith et al., 2012; Velthof et al., 2003). A meta-analysis by Zhou et al. (2017) of N_2O emissions from grain cropping systems showed that PL increased N_2O emissions by 45% compared to synthetic N fertilizers. This increase was attributed to manures providing N and labile organic C substrates that enhanced microbial activity of nitrifiers and denitrifiers, which may stimulate additional N_2O flux. Additionally, the increased microbial respiration could lead to increased O_2 consumption, creating anaerobic microsites favorable for denitrification and possible N_2O loss (Petersen et al., 1996). The Intergovernmental Panel on Climate Change (IPCC, 2006) has a default emission factor (EF) of 0.01-kg N_2O-N emitted for every 1-kg N organic amendments applied to managed soils. This EF has a wide range of uncertainty [0.003-0.03-kg N_2O-N (kg $N)^{-1}$] which demonstrates that N_2O measurements are quite variable due to environmental conditions and the complexity of the N cycle.

Placement of the PL below the soil surface should theoretically increase denitrification rates due to greater soil moisture and presence of labile C in PL facilitating microbial activity, leading to depletion of O_2 and formation of anaerobic microsites (Dell et al., 2011). The evaluation of subsurface banding PL on N_2O emissions is limited and has produced contrasting results. The most recent study found there were no differences between N_2O emissions of tillage-incorporated PL and subsurface banded PL in plots that were either bare ground or had a cereal rye (*Secale cereale* L.) cover crop when the PL was applied at a P-based application rate (Davis et al., 2019). In the same study, subsurface banded PL had increased N_2O emissions compared to tillage-incorporated PL in plots with either hairy vetch (*Vici villosa* Roth.) or cereal rye:hairy vetch mixture cover crop (Davis et al., 2019). The authors suggested the high C:N ratio of the cereal rye monoculture residue immobilized the inorganic N and likely reducing N available to denitrifiers. The opposite effect was noted with hairy vetch reside, which supplied an additional 102-163 kg N ha^{-1} and lower C:N ratio that would favor mineralization. Research by Nyakatawa et al. (2011) on a silt loam soil concluded that subsurface banded PL was a net sink for N_2O while PL broadcast on the surface or incorporated with tillage were net emitters of N_2O averaged over the calendar year when applied at 150 kg N ha^{-1}. Smith et al. (2012) had a 1-yr study investigating the effect of PL application placement on N_2O emissions in maize and reported that mean N_2O emissions from subsurface banding PL was nearly four times greater than PL surface broadcast on a sandy loam soil during the growing season at an application rate of 310 kg N ha^{-1}. The authors also noted that denitrification was limited without the addition of organic fertilizers due to inorganic fertilizers having limited N_2O emissions regardless of tillage or fertilizer placement.

1.4 Research Gaps

The variation in N_2O emission results from limited past research indicates that site specific fertilizer management practices need to be evaluated to mitigate N_2O emissions from agricultural soils. The previously mentioned studies that investigated subsurface banding PL and N_2O emissions only had one lateral subsurface PL placed between maize rows. Past research demonstrated subsurface banding of PL can improve nutrient utilization compared to traditional surface broadcast PL application in no-till systems such as maize, cotton, and forages. However, at the onset of this project there was no information about the effect that increasing the number of subsurface PL bands between maize rows could have on no-till maize yield, nutrient use, and ammonia volatilization. The objective of this study was to evaluate N_2O emissions, NH_3 volatilization, and maize performance when a single target N rate of PL is placed in one, two, or three lateral subsurface bands between maize rows.

CHAPTER 2. LATERAL SPACING OF SUBSURFACE POULTRY LITTER BANDS: EFFECT ON NITROUS OXIDE AND AMMONIA LOSS

2.1 Abstract

Nitrogen fertilization of agricultural soil stimulates nitrous oxide (N_2O) production, a potent greenhouse gas, and accounts for over 75% of the anthropogenic N_2O emissions globally. Best management practices for land application of animal manures as a source of N don't primarily address the effect they have on N_2O emissions. It is well documented that subsurface applied poultry litter (PL) reduces N losses by ammonia (NH_3) volatilization; however, the effect of this application method on N_2O emissions has been mixed. A two-year field experiment was initiated May 2014 on a Crider silt loam to determine if subsurface applying PL in multiple bands between maize (*Zea mays* L.) rows influenced N_2O emissions and NH_3 volatilization. Treatments consisted of an untreated control (UTC), urea ammonium nitrate (UAN, 32% N) surface banded (Fert), PL surface broadcast (PLBr), and three subsurface banded PL treatments. The subsurface PL treatments were 1 (PLSub1), 2 (PLSub2), and 3 (PLSub3) lateral bands in the inter-maize row area. Treatments receiving N amendments were added at 180 kg total N ha^{-1} each spring prior to maize planting. Nitrous oxide emission varied each growing season and N_2O pulses coincided with rainfall events larger than 1-cm following treatment application. Subsurface banding PL had significantly lower ($P < 0.1$) cumulative N_2O emissions than PLBr in 2014. The same trend occurred in 2015 with the PLSub2 treatment. Surface broadcasting PL had greater NH_3 volatilization than all PLSub treatments, which agrees with other studies. No differences were observed between PLSub treatments in 2014 and 2015 for cumulative N_2O emissions and NH_3 volatilization. These results suggested that subsurface banding PL can reduce N_2O emissions and conserve N compared to the traditional method of surface broadcasting PL; however, there was no advantage in applying PL in multiple subsurface bands.

2.2 Introduction

Nitrogen is the most critical nutrient for non-leguminous plants in crop production due to the requirement of N for optimal crop growth. This dependency on applying N to cropland has resulted in the agricultural sector being the primary source of global N_2O emissions. Nitrous oxide is a greenhouse gas that has 265 times the global warming potential of carbon dioxide (CO_2) over a 100-yr time frame, can persist in the atmosphere for 114 yr, and causes ozone layer depletion in the stratosphere. A recent report stated that agricultural soils accounted for 74% N_2O emissions and 4.5% of total greenhouse gas emissions in the United States (U.S. EPA, 2023).

Nitrous oxide is produced naturally in the soil through the biochemical processes of nitrification and denitrification (Hatfield, 2016; Hutchinson and Davidson, 1993;

Mosier et al., 2005). Emission of N_2O can arise under a wide range of soil conditions due to nitrification being an aerobic microbial process and denitrification occurring in anaerobic environments. Both soil processes can be influenced by many factors, including soil water content, inorganic N concentrations, available C, oxygen content, temperature, and pH.

Nitrification is the microbial oxidation of ammonium to nitrite (NO_2^-) by ammonia-oxidizing bacteria and ammonia-oxidizing archaea followed by oxidation of NO_2^- to nitrate (NO_3^-) by nitrite-oxidizing bacteria. Firestone and Davidson (1989) developed a 'Hole-in-the-Pipe' conceptual model that suggests the inefficient transfer of substrates at each oxidation stage of nitrification can produce N_2O as a by-product. In the first pathway for N_2O production, an intermediate product in the oxidation of ammonium to nitrite, hydroxylamine, can be directly oxidized to nitric oxide (NO) by hydroxylamine oxidoreductase and then NO can be further reduced to N_2O by nitric oxide reductase (Stein, 2011). A second pathway for N_2O production in the nitrification process is nitrifier denitrification in which NO_2^- is reduced by copper-containing nitrite reductase to NO which can be further reduced to N_2O by nitric oxide reductase (Wrage et al., 2001). Granli and Bockman (1994) reported that the proportion of N_2O to NO_3^- produced from nitrification will increase when there are decreases in O_2 and NH_4^+ concentrations and increases in in temperature and H_2O above field capacity.

Heterotrophic denitrification is a soil microbial respiratory process that reduces NO_3^- and NO_2^- to the gaseous forms NO, N_2O, and N_2, which can all be emitted during denitrification. Denitrification generally occurs in anaerobic environments when water-filled pore space of soil exceeds 60% and denitrifying bacteria carry out the reaction by using NO_3^- instead of oxygen as an electron acceptor in respiration. The enzymes nitrate reductase, nitrite reductase, nitric oxide reductase, and nitrous oxide reductase regulate the stepwise reduction of NO_3^- to N_2. Overall, total denitrification N losses increase when there is a decrease in soil oxygen and increase in soil temperature, available C, pH and NO_3^-. Velthof and Rietra (2018) stated that it is noteworthy to examine the ratio of N_2O loss to that of complete denitrification resulting in N_2 formation. Firestone and Davidson (1989) reported that increases in NO_3^-, NO_2^- and O_2 and decreases in C availability, pH, temperature, H_2O between 60 and 90% WFPS, and low N_2O reductase activity will likely increase the N_2O/N_2 ratio. This suggests that conditions not suitable for optimal total denitrification (low temperature, low pH, and increase in O_2) may result in a greater proportion of N_2O being emitted.

Land application of PL enriches the atmosphere with N_2O (Davis et al., 2019; Nyakatawa et al., 2011; Sistani et al., 2011; Sistani et al., 2019; Smith et al., 2012; Velthof et al., 2003). A meta-analysis by Zhou et al. (2017) of N_2O emissions from grain cropping systems showed that PL increased N_2O emissions by 45% compared to synthetic N fertilizers. The authors explained this increase was attributed to manures providing N and labile organic C substrates that enhanced microbial activity of nitrifiers and denitrifiers, which may stimulate additional N_2O flux. Additionally, the increased microbial respiration could lead to increased O_2 consumption, creating anaerobic microsites favorable for denitrification and possible N_2O loss (Petersen et al., 1996). The

Intergovernmental Panel on Climate Change (IPCC, 2006) has a default emission factor (EF) of 0.01-kg N_2O-N emitted for every 1-kg N organic amendments applied to managed soils. This EF has a wide range of uncertainty [0.003-0.03-kg N_2O-N (kg N)$^{-1}$] which demonstrates that N_2O measurements are quite variable due to environmental conditions, differences in sampling protocol, spatial variability, and the complexity of the N cycle.

Poultry litter is traditionally surface broadcast in no-till systems, which can leave the PL susceptible to NH_3 volatilization unless it is incorporated into the soil profile by rainfall shortly after application. Past studies show that NH_3 volatilization can generally account for up to 30% N loss of the TN applied from PL surface application (Brinson et al., 1994; Cabrera and Chiang, 1994; Cabrera et al., 1994; Pote and Meisinger, 2014; Sharpe et al., 2004). Ammonia volatilization not only creates an economic loss for the producer by reducing the nutrient value of the PL but can also negatively affect the environment. Environmental concerns associated with NH_3 loss to the atmosphere include contributing to acid rain (Sharpe et al., 2004), eutrophication from deposition of N into surface water bodies (Hutchinson and Viets, 1969), and aerosols when ammonia reacts with nitrates and sulfates in the atmosphere causing human respiratory issues and increasing global radiation (Behera et al., 2013). Additionally, NH_3 volatilization can result in indirect N_2O emissions by subsequent atmospheric deposition of NH_3 to terrestrial and aquatic ecosystems (IPCC, 2006).

Subsurface banding of PL is a recently developed technology to abate NH_3 volatilization in no-till cropping systems (Pote et al., 2011; Way et al., 2013). Past research shows that subsurface banding PL reduces N losses from NH_3 volatilization by greater than 88% in contrast to surface broadcast PL (Pote and Meisinger, 2014; Pote et al., 2011). The N conserved from mitigating NH_3 losses by subsurface banding PL has the potential to increase N_2O emissions during the growing season. Placement of the PL below the soil surface should theoretically increase denitrification rates due to greater soil moisture and presence of labile C in PL, facilitating microbial activity, and leading to O_2 depletion and formation of anaerobic microsites (Dell et al., 2011).

The evaluation of subsurface banding PL on N_2O emissions has been limited and produced conflicting results. The most recent study found there were no differences between N_2O emissions of tillage-incorporated PL and subsurface banded PL in plots that were either bare ground or had a cereal rye (*Secale cereale* L.) cover crop when the PL was applied on a P-based application rate (Davis et al., 2019). However, in plots with either hairy vetch (*Vici villosa* Roth.) or cereal rye:hairy vetch mixture, the subsurface banded PL had increased N_2O emissions in contrast to tillage-incorporated PL (Davis et al., 2019). The authors suggested that the high C:N ratio of the cereal rye monoculture residue immobilized the inorganic N and likely reducing N available to denitrifiers. The opposite effect was noted with hairy vetch reside, which supplied an additional 102-163 kg N ha^{-1} and lower C:N ratio that would favor mineralization. Research by Nyakatawa et al. (2011) on a silt loam soil concluded that subsurface banded PL was a net sink for N_2O while PL broadcast on the surface or incorporated with tillage were net emitters of N_2O averaged over the calendar year when applied at 150 kg N ha^{-1}. Smith et al. (2012)

had a 1-yr study investigating the effect of PL application placement on N_2O emissions in maize and reported that mean N_2O emissions from subsurface banding PL was nearly four times greater compared to PL surface broadcast on a sandy loam soil during the growing season at an application rate of 310 kg N ha^{-1}. The authors also noted that denitrification was limited without the addition of organic fertilizers due to inorganic fertilizers having limited N_2O emissions regardless of tillage or fertilizer placement.

The variation in N_2O emission results from limited past research indicates that site specific fertilizer management practices need to be evaluated to mitigate N_2O emissions from agricultural soils. The previously mentioned studies that investigated subsurface banding PL and N_2O emissions only had one lateral subsurface PL placed between maize rows. The objective of this study was to evaluate N_2O emissions and NH_3 volatilization when a single target N rate of PL was placed in one, two, or three lateral subsurface bands between maize rows.

2.3 Materials and Methods

2.3.1 Site Description

A field plot study (2014-2015) was conducted in Bowling Green KY (36º55’52” N; 86º28’12” W; altitude 167-m) at the Western Kentucky University Agriculture & Research Education Center. The region has a warm temperate climate with typical annual precipitation of 127-cm and mean temperature of 15.1ºC. Climatological data was collected throughout the growing seasons from a nearby Kentucky Mesonet weather station located within 30-m of the study (Mesonet, 2023). The site was on a Crider silt loam soil (Fine-silty, mixed, active, mesic Typic Paleudalfs) with 8.2% sand, 69.9% silt, and 21.9% clay as analyzed by hydrometer method (Gee and Or, 2002). The plot area had previously been cropped in a no-till maize/wheat (*Triticum aestivum* L.)/soybean [*Glycine max* (L.) Merr.] rotation for at least 8-yr.

2.3.2 Experiment Design and Treatment Establishment

The experiment design was a randomized complete block with three replicates in a no-till maize system. The study site in the second year was moved to an adjacent portion of the field to eliminate residual effects of the PL. Experimental units were 6.1-m by 9.1-m to accommodate 8 rows of no-till maize at 76-cm spacing. The six treatments evaluated in this study consisted of an untreated no N control (UTC), urea ammonium nitrate (UAN, 32%) surface banded (Fert), PL surface broadcast (PLBr), and 3 subsurface banded PL treatments. Treatments receiving N amendments were applied preplant at the rate of 180-kg total N ha^{-1} on 21 May 2014 and 1 May 2015. This N application rate equated to 5.96 and 5.41 Mg PL ha^{-1} for 2014 and 2015, respectively, based on the TN content of the litter (Table 2.1).

The Fert treatment was surface banded 25-cm from maize rows using a calibrated tractor power take-off-driven boom sprayer (T-30G; Bellspray Inc., Opelousas, LA). The sprayer was equiped with flat fan spray nozzle tips (TP8006-VS; TeeJet Technology, Glendale Heights, IL) turned 90° so the spray pattern was perpendicular to the spray boom. Additionally, the Fert treatment received supplemental P and K fertilization to match that of the PL treatments; 57 kg P ha^{-1} and 150 kg K ha^{-1}, and 47 kg P ha^{-1} and 187 kg K ha^{-1} in 2014 and 2015, respectively.

The subsurface banded PL treatments were 1 (PLSub1), 2 (PLSub2), and 3 (PLSub3) lateral PL bands in the inter-maize row area (Figure 2.1). Each subsurface PL band supplied 100%, 50%, or 33.33% of the total N rate for PLSub1, PLSub2, or PLSub3, respectively. The PLSub1 treatment had 76-cm lateral spacing which resulted in a single PL band offset 25-cm from each maize row. The PLSub2 treatment had alternating 25-cm and 51-cm lateral spacing resulting in two subsurface PL bands offset 25-cm on both sides of each maize row. The PLSub3 treatment had lateral spacing of 25-cm which resulted in two inter-row PL subsurface bands offset 13-cm on both sides of each maize row and one PL subsurface band offset 38-cm from maize rows. The PLSub treatments were applied using an experimental tractor-mounted PL applicator implement (Way et al., 2013) that placed PL in trenches that were approximately 4-cm wide and 8-cm below the soil surface. The applicator was calibrated by adjusting the speed of the delivery conveyors, the height of the conveyor flow gates, and tractor ground speed. To reduce treatment differences from compaction, the tractor and PL loaded implement was driven over each plot an equal number of passes.

Maize was planted on 21 May 2014 and 1 May 2015 following treatment application at a seeding rate of 78,500 seeds ha^{-1} and 5.7-cm depth using a four-row no-till planter (7200 MaxEmerge 2; Deere & Company, Moline, IL). The maize hybrid seed for both growing seasons was NK N70J-4011 RR/*Bt* (Syngenta, Basel, Switzerland) and has a maturity rating of 112 days. In-season weed control consisted of atrazine 4L at 2.2 kg a.i. ha^{-1} and 41% glyphosate at 1.7 kg a.i. ha^{-1} applied with a CO_2 pressurized backpack sprayer (T4; Bellspray Inc., Opelousas, LA) equiped with flat fan spray nozzles (TP8002-VS; TeeJet Technology, Glendale Heights, IL).

2.3.3 Poultry Litter

Poultry litter used in this experiment was acquired from broiler production facilities in South Central Kentucky and nutrient content was determined on a wet basis prior to treatment application. Initially, plans were to use PL from the same broiler facility, however in 2015 the moisture content of the original broiler producer's PL was greater than 40%. This created an issue with the subsurface PL banding implement accurately applying treatments due to clogging problems with the conveyor system when moisture contents exceed 35%, as noted by Way et al. (2013). The PL used in 2015 came from another local broiler facility that had been stored in a dry stack shed since fall 2014. In 2014, no issues were experienced with accurate calibration of the PL subsurface banding implement despite a 37.5% moisture content.

Moisture content of the PL was determined by drying 20-g as-collected PL at 110°C for 24-hr, following procedures outlined in Hoskins et al. (2003). Poultry litter pH was measured in a 1:5 litter/water mixture using a digital pH meter (Orion 3 STAR pH meter and ROSS Ultra pH/ATC probe; Thermo Scientific, Beverly, MA). Microwave assisted acid digestion (U.S. EPA, 2007) was used to analyze P and K in the PL. In this method, 0.5-g PL was mixed with 9-mL HNO_3 and 3-mL HCl in microwave digestion vessels and predigested in a fume hood for 60-min. The vessels were then placed in a MARS5 microwave (CEM Corp., Matthews, NC.) to ramp the sample mixture up to 175°C over 6.5-min and then held at 175°C for an additional 12-min. The digested sample mixture was filtered through quantitative grade filter paper (Q2, Fisher Scientific, Hampton, NH) before P and K analysis using an inductively coupled plasma optical emission spectrophotometer (ICP-OES) (Vista-Pro; Varian Inc, Palo Alto, CA). An adapted version of Keeney and Nelson (1996) was used to determine NH_4^+-N and NO_3^--N in the PL. Briefly, PL was extracted with 2 *M* KCl using 2-g as-collected PL in a 1:30 PL/extractant ratio, shaken at 150-rpm for 20 min, filtered through quantitative grade filter paper, and diluted 100-fold. The diluted sample extracts were analyzed on a Lachat QuikChem 8000 FIA+ flow injection instrument (Hach, Loveland, CO) using QuikChem methods 10-107-04-1-A and 12-107-06-2-A for NO_3^--N and NH_4^+-N, respectively. A Vario Max CN analyzer (Elementar Americas Inc, Mt. Laurel, NJ) was used to determine TN and TC in the as-collected PL by automated high temperature combustion and an integrated thermal conductivity detector (TCD).

2.3.4 Nitrous Oxide Measurements

Nitrous oxide emissions between the soil surface and atmosphere were measured using static, vented chambers fabricated from aluminum metal (Hutchinson and Mosier, 1981; Livingston and Hutchinson, 1995; Mosier et al., 1991). The chambers consisted of a semi-fixed anchor (38-cm width by 76-cm length) that was forced in the soil surface to a depth of 10-cm and a removable lid that had a vent tube and rubber septa for sampling with a syringe and needle.

Background N_2O emissions were measured from each replication prior to treatment application each year. Directly following treatment application and maize planting, one chamber anchor was installed between rows five and six of each plot and positioned so the length of the chamber covered the entire inter-row area to include all subsurface PL bands. Nitrous oxide emissions were sampled 22 times each year following treatment application using the same procedures outlined by Mosier et al. (2005). Measurements were generally made mid-morning one to three times per week for most of the growing season until N_2O emissions subsided to background levels, then sampling occurred once every two weeks.

At each N_2O sampling date, the 10-cm tall lids were placed in a channel on the semi-fixed anchors filled with water to create an airtight seal. With the lid on, the sampling volume of the chambers was 46-L. Gas samples were collected from the chambers with a 60-mL disposable syringe fitted with a needle (0.6-mm by 25-mm) at intervals of 0, 15, and 30-min after placement of lids onto the semi-fixed anchors. Forty milliliters of gas sample was injected into pre-evacuated 20-mL glass vials sealed with gray butyl septa and aluminum crimp tops. This over-pressurized technique was utilized by Smith and Owens (2010) to prevent contamination from ambient air if any leaks existed.

Gas samples were analyzed for N_2O within 24-hr of collection using a gas chromatograph (CP 3800; Varian Inc., Palo Alto, CA) equipped with a ^{63}Ni electron capture detector and a Combi-Pal headspace autosampler (CTC Analytics, Zwingen, Switzerland). A known concentration of a custom-mix standard gas was analyzed for every 25 unknown samples to serve as a quality control standard. Nitrous oxide flux was calculated from the linear or non-linear (Hutchinson and Livingston, 1993) increase in concentration over time in the chamber headspace, selected according to diffusion effects by an algorithm developed by Hutchinson and Mosier (1981).

Estimates of daily N_2O fluxes between sampling dates were calculated using linear interpolation from two adjacent sampling events and summation of these daily values were used to calculate cumulative N_2O emissions for each growing season (Halvorson et al., 2010; Sistani et al., 2011; Sistani et al., 2010). Nitrous oxide EF is the percentage of N inputs that are emitted as N_2O over the growing season after subtracting N_2O emissions from an unfertilized control and was calculated based on the following equation:

$$N_2O\text{-}N\ EF\ (\%) = [(N_2O\text{-}N_{\text{fertilized soil}} - N_2O\text{-}N_{\text{unfertilized soil}})/N_{\text{applied}}] * 100$$

Volumetric soil water content (0- to 5-cm depth) and soil temperature (5-cm depth) were recorded at each N_2O flux sampling event using combination soil moisture and temperature probes (5TM; Decagon Devices Inc., Pullman, WA). Water-filled pore space (WFPS) was determined using a particle density of 2.65 Mg m^{-3} and soil bulk density (measured by core method to 5-cm depth) as outlined by (Linn and Doran, 1984).

2.3.5 Ammonia Volatilization Measurement

Open chamber NH_3 traps were used to quantify NH_3 volatilization loss based on research conducted by Jantalia et al. (2012). This method employs 2-L polyethylene terephthalate (PET) soda bottles and polyfoam strips (25-cm length by 2.5-cm width by 0.3-cm thick) soaked in a sulfuric acid solution [1 mol L^{-1} H_2SO_4 plus 4% (v/v) glycerol] to trap NH_3 loss. The bottom of PET bottles were removed and inversely suspended with wire 2-cm above the top opening of the PET bottle to prevent precipitation from contacting the acid-soaked foam strip and permit free-air circulation. The PET bottle chambers were 26-cm in length, 10-cm in diameter, and covered an area of 79-cm^2 on the soil surface. A diagram of the open chamber individual components and final construction can be found in research by Jantalia et al. (2012).

A single acid-soaked foam strip was suspended inside the PET chamber from the bottle lid with a wire hook while the lower end of the foam strip remained in a 60-mL plastic container containing 50-mL of the H_2SO_4 and glycerol solution, also suspended off the soil surface. To maintain stability of the open chambers in plots, three metal stakes (0.5-cm diameter and 23-cm length) were placed 10-cm into soil around the outside perimeter of the chamber and secured with 0.4-cm thick rubber bands placed around the bottle and metal stakes.

Acid trap chambers were installed on the same day following the application of treatments and planting of maize. The UTC and PLBr treatments had one chamber placed randomly in the inter-row area of each plot, whereas Fert, PLSub1, and PLSub2 had one chamber positioned colinear with the fertilizer band in each plot. The PLSub3 treatment had two chambers for each plot, one located over a PL band nearest to the maize row and the second positioned over the middle band located furthest from the maize row.

In 2014, the acid traps were collected on Day 3, 6, 9, 14, 20, 26, 33, 40, 49, 55, 65, 75, 84, 97, 110, 124 and 131 following treatment application on 21 May. Collection dates in 2015 were on Day 3, 6, 10, 13, 18, 26, 35, 45, 56, 68, 81, 102, 118, and 132 after treatment application on 1 May. At each sampling date the polyfoam strip and container with acid solution are collected, replaced with new acid traps, and then taken back to the lab to be stored at 4°C. The foam strips and containers were rinsed with 2 *M* KCl until brought to a volume of 250-mL using a volumetric flask. Forty mL of this extract was filtered through a quantitative grade filter paper and frozen at -20°C until analysis using flow injection analysis with QuikChem method 12-107-06-2-A for NH_4^+-N.

The NH_3 lost during the collection dates is calculated by multiplying the NH_3-N concentration from the analysis by the 250-mL of total extract and then dividing by the soil surface area covered by each chamber. Additionally, the NH_3-N loss for banded plots was calculated based on the weighted average of the NH_3-N loss in the area over the fertilizer bands and the NH_3-N emission from the UTC for areas not affected by fertilizer bands. Cummulative NH_3-N loss for the growing season was calculated by summing NH_3-N volatilization loss from each collection period. Ammonia emission factor (EF) is the percentage of N inputs that are emitted as NH_3 over the growing season compared to an untreated control and was calculated based on the following equation:

$$NH_3\text{-N EF } (\%) = [(NH_3\text{-N}_{\text{fertilized soil}} - NH_3\text{-N}_{\text{unfertilized soil}})/N_{\text{applied}}] * 100$$

2.3.6 Soil Sample Collection and Analysis

Background soil samples were randomly collected to a depth of 10-cm throughout each plot prior to treatment application on 19 May 2014 and 28 April 2015 using a 2.54-cm inside diameter soil probe. Soil cores were collected on N_2O sampling dates following treatment application, which equated to 22 sampling events each year. The UTC and PLBr treatments were sampled randomly across the plot area excluding the border rows following treatment application. Plots receiving banded treatments (Fert and PLSub) had a nested soil sampling scheme that produced 3, 3, or 5 subsets for 1, 2, or 3 band treated plots, respectively (Figure 2.1). The Fert and PLSub1 plots had 3 soil cores taken; 1.) 25-cm from the maize in the fertilizer band, 2.) in the middle of the 25-cm spacing between the maize row and fertilzer band, and 3.) in the middle of the 51-cm spacing between the maize row and fertlizer band. The PLSub2 treatment had 3 soil cores taken; 1.) in the middle of the distance between the maize row and nearest PL band, 2.) in the PL band, and 3.) in the middle of the distance between PL bands which was approximately 38-cm from maize rows. The PLSub3 plots had 5 soil cores taken; 1.) in the middle of the distance between the maize row and nearest PL band, 2.) in the nearest PL band from the maize row, 3.) in the middle of the distance between the nearest and furthest PL band from maize rows, 4.) in the furthest PL band from the maize rows, and 5.) an additional core similar to core 3 however on the opposite of the PL band in core 4.

The nested samples were collected in three random locations within plots, composited based on location sampled between the inter-row area, analyzed as individual samples, and nutrient concentrations calculated for each plot based on a weighted average of individual subsamples to represent the inter-row maize area. The following equations demonstrate how the nutrient concentration averages were calculated for each banding treatment and subscripts represent soil sample location (SSL) within the inter-row area for each treatment as previously mentioned.

Fert and PLSub1

$$\text{Plot}_{AVG} = (\text{SSL}_1 + \text{SSL}_2 + \text{SSL}_3) / 3$$

PLSub2

$$\text{Plot}_{AVG} = (2\text{SSL}_1 + 2\text{SSL}_2 + \text{SSL}_3) / 5$$

PLSub3

$$\text{Plot}_{AVG} = (2\text{SSL}_1 + 2\text{SSL}_2 + \text{SSL}_3 + \text{SSL}_4 + \text{SSL}_5) / 7$$

Composited soil samples from background and N_2O sampling dates were placed in zip seals bags, homogenously mixed manually, and half the sample transferred to another zip seal bag to be stored at 4°C for inorganic N determination. As-collected soil samples stored at 4°C were analyzed for NO_3^--N and NH_4^+-N using flow-injection analysis after extraction with 2 *M* KCl (Keeney and Nelson, 1996). Briefly, soil was extracted with a 1:10 soil/2 *M* KCl extraction ratio, shaken at 150 rpm for 20-min, filtered through quantitative grade filter paper (Q2, Fisher Scientific, Hampton, NH), and analyzed using flow injection analysis with QuikChem methods 10-107-04-1-A and 12-107-06-2-A for NO_3^--N and NH_4^+-N, respectively. The remainder of the soil collected at background each year was allowed to air dry, ground with a soil crusher (Dynacrush; Custom Laboratory Equipment Inc., Orange City, FL), and sieved to pass a 2-mm mesh screen. These samples were analyzed for soil pH using a 1:1 soil/0.01 *M* $CaCl_2$ ratio mixed for 10-min and after a 10-min waiting period, the solution was analyzed with a pH meter and electrode. Total N and C were obtained using 1-g of air-dried sample measured by automated dry combustion with a VarioMax CN analyzer. Extractable P and K were assessed using Mehlich-3 (M3) extractant and 2-g soil in a 1:10 soil/M3 ratio, shaken for 30-min at 150 rpm, and filtered through quanititative grade filter paper before analysis using ICP-OES (Mehlich, 1984).

2.3.7 Statistical Analysis

Data analysis among treatments was subjected to a generalized linear mixed model analysis of variance (SAS Institute Inc., 2013). The Kenward-Rodger method was used to calculate degrees of freedom. Data for each year were further analyzed individually if there was a significant year and treatment interaction ($P < 0.1$). Means were separated according to Fisher's Protected LSD at $\alpha = 0.1$ to make statistical comparisons.

2.4 Results and Discussion

2.4.1 Environmental Factors

Monthly mean air temperatures ranged from 14.3°C to 25.7°C with an average of 23.0°C in 2014 and 23.4°C in 2015 (Figure 2.2). The 2014 and 2015 growing season were generally cooler than the 15-yr means for Warren County, KY (National Centers for Environmental Information, 2022). Daily mean air temperature and relative humidity are in Figure 2.3 (a) and Figure 2.4 (a) for the 2014 and 2015 growing seasons, respectively. Air temperatures ranged from 13.8°C to 29.2°C with an average of 23.0°C in 2014. In 2015, average air temperatures were slightly higher at 23.4°C with a range of 10.8°C to 28.4°C. Average daily air temperatures were generally cooler for the first 40 days after planting in 2015 compared to 2014 which resulted in 2.3% fewer growing degree days (GDD) 115 days following planting. Relative humidity was similar between years with an average of 73%, a maximum of 97% and a minimum of 60%.

Soil temperature and water filled pore space (WFPS) for sampling dates in 2014 are in Figure 2.3 (b) and for sampling dates in 2015 are in Figure 2.4 (b). Average soil temperatures at 5-cm depth were nearly 10% lower in 2015 than 2014, which is likely because the experiment started 20 days earlier in 2015. Soil temperature ranged from 12.6°C to 26.4°C across the years. In 2015, soil temperatures at 5-cm depth were lower for 6-d following treatment application than the initial soil temperature at treatment application in 2014, which is mainly due to an earlier calendar year application date in 2015.

The timing and magnitude of precipitation varied between the two growing seasons. Daily and cumulative precipitation for 2014 and 2015 are in Figure 2.5 (a). Cumulative precipitation for both years was below the 30-yr average (53.8-cm) for Bowling Green, KY at similar time periods. In 2014, cumulative precipitation was 27.3-cm which was 47% lower than the total of 51.6-cm in 2015. The 2015 growing season had 53 rain events compared to 36 rain events in 2014. Rain didn't occur until 12 and 10 days after treatment application for 2014 and 2015, respectively. Average WFPS was 9.6% greater in 2015 [Figure 2.4 (b)] than 2014 [Figure 2.3 (b)]. There were periods during the middle of each growing season when the maize may have been water stressed, with 2014 being more extreme with an observation low of 26% WFPS compared to 42% in 2015.

2.4.2 Nitrous Oxide Emissions

Nitrous oxide was not consistently emitted through the growing seasons [Figure 2.5 (b)]. The N_2O emissions increased rapidly following N application, particularly PLSub treatments in 2014. Chantigny et al. (2010) reported that liquid swine manure created higher N_2O fluxes, likely facilitated by available C in the manure, and found there was a positive linear relationship between water extractable organic C and N_2O emissions in a loam soil. The N and C substrates found in PL when concentrated in subsurface bands may have stimulated nitrification and denitrification, resulting in N_2O emission particularly early after manure application in this study. In 2014, PLSub2 and PLSub3 had N_2O fluxes that were numerically higher than PLSub1 shortly following application, which could be attributed to greater accessibility of N and C substrates for nitrifiers and denitrifiers organisms in the soil when PL is placed in multiple bands. This trend wasn't as pronounced in 2015, possibly because soil temperatures were 6.4°C cooler following application, which may have slowed the microbially mediated process of nitrification coupled with the 2015 poultry litter source having 56% lower ammonium concentration (Table 2.1) compared to 2014.

Nitrous oxide fluxes subsided to near background levels around 12 days after application for both growing seasons. However, shortly thereafter, a secondary spike in N_2O fluxes was observed following a 27-mm and 57-mm rainfall on 10 June 2014 and 17 May 2015, respectively. The WFPS after these rainfall events was 86% in 2014 [Figure 2.3 (b)] and 90% in 2015 [Figure 2.4 (b)], creating an anaerobic environment that could have favored denitrification, resulting in elevated N_2O emissions. On these dates, the surface treatments of Fert and PLBr had the highest observed N_2O flux rates for these respective treatments each year. This is likely due to it being the first appreciable rainfall to leach NO_3^- below the soil surface where it could be used as a substrate for denitrification. The microbial process of denitrification stimulate N_2O emissions when there is increased NO_3^- concentrations, high amounts of available C, and when O_2 becomes limited (Cabrera and Chiang, 1994; Linn and Doran, 1984; Nömmik, 1956).

In 2014, PLSub2 had the greatest single N_2O emission at 807.8 ug $N_2O\text{-}N\ m^{-2}\ h^{-1}$ the day after treatment application. At 18 days after treatment application in 2015, the Fert treatment had 832.6 ug $N_2O\text{-}N\ m^{-2}\ h^{-1}$, which was the largest N_2O flux of all observations. When averaged across treatments, 2014 had an average N_2O flux of 87.4 ug $N_2O\text{-}N\ m^{-2}\ h^{-1}$, which was significantly higher ($P < 0.1$) than that in 2015 (70.7 ug $N_2O\text{-}N\ m^{-2}\ h^{-1}$) (data not shown). With 2015 having nearly twice the precipitation as 2014, N_2O flux would have been expected to be greater in 2015 if denitrification was the main process affecting N_2O emissions. This suggests that nitrification probably played a significant role in controlling N_2O flux. In an incubation study, Fitzgerald (2019) reported N_2O-N production from surface applied PL and PL incorporated 4-cm deep in a Crider silt loam soil at 36% WFPS was largely due to nitrification rather than denitrification. She noted N_2O emissions followed the same pattern as nitrification rates, which increased after treatment application and declined after day 7. A similar trend was observed in the current study according to soil inorganic N concentrations at 10-cm taken at N_2O sampling dates (Figure 2.6). Overall, soil NH_4^+-N concentrations for N amended plots steadily decreased while NO_3^--N concentration increased for the first 45-d following treatment application which would indicate nitrification occurring. During this period most N_2O was emitted and then declined, similar to that observed in previous studies (Chantigny et al., 2010; Davis et al., 2019; Halvorson et al., 2010; Sistani et al., 2019). This decline aligns with periods during the middle of the growing seasons when the maize began rapid removal of plant available N from the soil and WFPS began to drop below 60% [Figures 2.3 (b) and 2.4 (b)] which likely caused a reduction in mineralization of organic N and nitrification.

The N_2O fluxes occurring within 45-d after treatment application accounted for 63% of the total N_2O emissions where the WFPS was 74% averaged across years and treatments. Nitrification-related pathways for N_2O production are favorable at 30-70% WFPS compared to denitrification, which dominates N_2O emissions in soils with >80% WFPS (Braker and Conrad, 2011; Huang et al., 2014). Nitrous oxide can be emitted as a by-product from two pathways in the nitrification process, primarily when conditions inhibit transfer of substrates causing inefficiency in nitrification, which is likely the case in this study's situation when WFPS exceeded 60%. Firestone and Davidson (1989) explained that this inefficiency may lead to accumulation of toxic NO_2^- for NH_3 oxidizers, which may use NO_2^- as an electron accepter when O_2 is limited to form NO which can be further reduced to N_2O. Additionally, suboptimum oxidation of NH_4+ to NO_2^- in nitrification may lead to nitrifiers oxidizing the intermediate product, NH_2OH, to NO and further reduced to N_2O (Lazcano et al., 2021). The relationship between WFPS and N_2O production/consumption is complex because it influences not only O_2 availability, but also the diffusion of nutrients within the soil and microbial activity (Hu et al., 2015). The N_2O emissions declined to near background levels towards the end of each growing season.

2.4.3 Cumulative Nitrous Oxide Emissions

Annual cumulative growing season N_2O emissions were significantly greater for all N treatments compared to that of UTC except for PLSub2 in 2015 (Table 2.2). Average cumulative N_2O emissions were 1.90 kg N_2O-N ha^{-1} in 2014 and 1.84 kg N_2O-N ha^{-1} in 2015. Subsurface banding of PL had significantly lower cumulative N_2O emissions than broadcasting (PLBr) in 2014. PLSub2 was the only PLSub treatment to continue this trend in 2015; however, all PLSub treatments had numerically lower cumulative N_2O emissions than PLBr. These results contradict findings by Smith et al. (2012) that showed subsurface banded poultry litter had significantly greater mean N_2O fluxes than surface applied poultry litter when averaged across tillage treatments for a fine sandy loam. The contrast in results could be attributed to the difference in soil texture and the depth at which poultry litter was subsurface banded. Smith et al. (2012)

reported a 4-cm distance between the soil surface and top of the subsurface poultry litter band compared to the 8-cm achieved in this this study. Velthof et al. (2003) showed that liquid pig manure placed at 10-cm depth resulted in N_2O emissions that were 47% and 27% lower than placement at 5-cm depth and on the surface in a sandy soil, respectively. The increased residence time and longer diffusion paths of N_2O to the atmosphere at the deeper depth may have increased the chance of N_2O being reduced to N_2 (Velthof et al., 2003).

Subsurface banding poultry litter reduced cumulative N_2O emissions by 15% and 23% compared to PLBr in 2014 and 2015, respectively. Increasing the number of subsurface poultry litter bands between corn rows did not significantly affect cumulative N_2O emissions in either growing season. The absence of differences in cumulative N_2O emissions between the PLSub treatments could be attributed to possible similarities in nitrification rates amongst treatments and enhanced reduction of N_2O to N_2 by placing the PL 8-cm below the soil surface. The enhanced reduction of N_2O is likely due to the finer textured soil used in this experiment compared to that studied by Velthof et al. (2003) which may have resulted in greater tortuosity and decreased gas diffusion. The greater the diffusion path for N_2O while in the soil solution increases the chance that the N_2O will be reduced to N_2 before emission to the atmosphere (Velthof et al., 2003).

2.4.4 Nitrous Oxide Emission Factor

Differences between N_2O EF mainly reflect the differences among cumulative N_2O emissions (Table 2.2). The sole outlier was PLSub1 in 2014, which did not have a significantly lower N_2O EF when compared to PLBr. Increasing the number of subsurface PL bands between maize rows did not significantly affect the N_2O EF. Emission factors ranged from 0.54% to 0.77 % in 2014 and 0.31% to 0.89% in 2015. These values were lower than the EF default value of 1% for the Intergovernmental Panel for Climate Change (IPCC) Tier I methodology used to estimate annual N_2O-N emissions from N fertilizer application to arable soils. However, they fall within the uncertainty range of 0.3-3% associated with the EF default value (De Klein et al., 2006). Previous researchers have reported a range of 0.2 to 5.8% N_2O emissions per kilogram of N applied as poultry litter (Akiyama et al., 2004; Cabrera et al., 1994; Davis et al., 2019; Sistani et al., 2011; Sistani et al., 2019; Thornton et al., 1998; Watts et al., 2015a). Thornton et al. (1998) and Watts et al. (2015a) reported losses of 1% and 1.5%, respectively, of total N applied in a field study as N_2O emissions whereas Sistani et al. (2011) noted losses of 5.8% for poultry litter surface broadcast. Large variability in N_2O EFs has been attributed to soil aeration, which has been noted as a major factor influencing whether nitrification (aerobic) or denitrification (anaerobic) dominates (Bouwman, 1996; Rochette et al., 2008). Soil moisture and temperature, mineralizable organic C, concentrations of NO_3^- and NH_4^+, and soil pH are additional factors noted by Bouwman (1996) that regulate the microbial processes of nitrification and denitrification.

2.4.5 Ammonia Emissions

The greatest NH_3 volatilization losses occurred within the first two sampling dates in 2014 and 2015 (Figure 2.7). The PLBr and Fert treatments had elevated NH_3 emissions that subsided to baseline levels within 35-d following treatment application. The University of Kentucky (Ritchey and McGrath, 2020) recommends fertilizers containing urea be incorporated into the soil by mechanical means or precipitation within two days following application to reduce NH_3 losses. Ammonia, once incorporated below the soil surface, is quickly hydrolyzed in the soil solution to form NH_4^+ which is then subject to nitrification if conditions are favorable. Rain able to leach the surface applied N treatments into the soil was not recorded until 20 days following application in 2014 and 15 days after application in 2015. These conditions left the surface applied N treatments susceptible to NH_3 volatilization, which was evident with the Fert treatment, which consisted of 35% urea, in 2014 and 2015. The Fert treatment had the highest single sample date observations for NH_3 emissions for 2014 and 2015 at 3.41 kg and 4.14 kg NH_3-N ha^{-1}, respectively. Peak losses generally occur within the first 7-d following application, however Drury et al. (2017) noted it can be prolonged for up to 15-d when minimal precipitation occurs following N application, which was the case with our study. Subsurface applied PL treatments followed the same NH_3 emission pattern as UTC during the growing seasons and there weren't noticeable differences between the PLSub treatments at sampling dates.

Results from both years indicate that nitrogen source and poultry litter application method affected cumulative NH_3 volatilization and NH_3 emission factors (Table 2.3). Subsurface banding of PL significantly lowered cumulative NH_3 losses when compared to PLBr and Fert, while being consistently similar to that of UTC. The Fert treatment had the highest loss of N applied at 5.46% averaged across both years and was four times greater than that of PLBr. Jantalia et al. (2012) reported UAN NH_3 losses of 3.6% of total N applied and noted that minimal NH_3 volatilization occurred when irrigation water was applied the day following N application. Over the two years of the study, the NH_3 loss from PLSub was completely eliminated compared to PLBr. These results suggest there was complete closure of PL under the soil surface by subsurface banding, therefore minimizing exposure to the atmosphere and potential NH_3 volatilization. These outcomes agree with previous research studies that showed greater than 84% reduction of NH_3 losses when PL was subsurface applied compared to traditional surface broadcast (Liu et al., 2016; Moore et al., 2011; Pote and Meisinger, 2014; Pote et al., 2011). The NH_3 emission factor of 0.9% for PLBr in 2015 was nearly half of the amount observed in 2014, 1.8%. This decrease was likely due to lower NH_4^+-N concentration of the PL in 2015 combined with lower soil and air temperature following treatment application that growing season.

2.4.6 Soil Inorganic Nitrogen

Soil NO_3^--N and NH_4^+-N concentrations for N amended treatments followed a typical rise-and-decline pattern following N application and maize N uptake (Figure 2.6). This trend was most clear with the Fert treatment because its composition was 45% ammonium nitrate and 35% urea, which is readily available for plant uptake shortly following application. Soil NH_4^+-N concentrations dropped rapidly within the first 30 days following treatment, which is likely due to nitrification to NO_3^--N. All PL treatments had similar patterns of soil NO_3^--N and NH_4^+-N concentrations throughout the growing season, except PLSub1, which had elevated NH_4^+-N values early in 2014 and 2015.

The PL concentrated in a single band may possibly had increased N mineralization, which is also supported by slightly higher soil NO_3^--N concentrations 3-4 weeks following treatment application compared to the other PL treatments. This hypothesis is supported by PLSub1 having significantly higher average soil NH_4^+-N concentrations across sampling dates in 2015 compared to the other PL treatments (Table 2.4). This trend was also observed in 2014, however, the effect wasn't significant.

Soil NO_3^--N concentrations remained steady or increased for N amended plots until 30-d following treatment application when maize N demand intensified. There was a delayed increase in soil NO_3^--N concentrations for PL treatments after N application, which appeared to be better aligned with corn N demands compared to Fert that essentially has 100% plant available N at application and could potentially reduce N losses. Bender et al. (2013) studied nutrient uptake in modern maize hybrids and reported that maximum N uptake rates occurred between the V10-V14, which is generally 7 to 9 weeks after maize emergence. Soil NO_3^--N has been shown to be a strong predictor for N_2O emission (Chantigny et al., 2010; Weier et al., 1991). However, across treatments there were no significant correlations between soil NO_3^--N or NH_4^+-N concentrations and observed N_2O production ($R^2 = 0.015$ and 0.028 in 2014, $R^2 = 0.094$ and 0.021 in 2015, respectively). Toward the end of each growing season, soil NO_3^--N and NH_4^+-N concentrations for all treatments returned to background values.

Average soil NO_3^--N concentrations at 0-10-cm in 2014 were 36.1 mg NO_3^--N kg^{-1} and in 2015 were 19.1 mg NO_3^--N kg^{-1} (Table 2.4). This could be attributed to nearly twice the amount of precipitation in 2015, which could have leached NO_3^--N through the soil profile beyond the 10-cm sampling depth. Additionally, pre-treatment background soil concentrations for 2015 were 14.1 mg NO_3^--N kg^{-1} compared to 25.1 mg NO_3^--N kg^{-1} in 2014. The higher initial NO_3^--N concentrations in 2014 may have resulted from residual N following the 2013 corn growing season, which had a 224 kg N ha^{-1} application rate compared to the 180 kg N ha^{-1} in this experiment. The Fert treatment had significantly greater NH_4^+-N, NO_3^--N, and total inorganic N values for both growing seasons compared to UTC and the PL treatments. This was expected because 100% of the N in Fert is readily available to the maize during the growing season compared to PL, which is generally estimated to have between 45-60% of the N available for plant uptake (Rasnake et al., 2000). This range of N availability for PL depends on PL composition, application method, application timing, and N mineralization rate.

The PL treatments had significantly greater average soil NO_3^--N concentrations in both growing seasons and total inorganic N in 2014 compared to UTC. PLSub1 had higher average soil NH_4^+-N and total inorganic N compared to PLBr in 2015. These results may indicate that a greater N mineralization rate was attained by subsurface banding PL in one band rather than broadcasting on the surface. Fitzgerald (2019) found in an incubation study that incorporated PL had significantly higher mineralization rates compared to surface broadcasting. She noted that incorporating PL increased the access of microorganisms to the PL therefore resulting in a higher N mineralization rate. Additionally, in this case the increase in average inorganic N values of PLSub1 could be due to N conservation by reducing the amount of NH_3-N lost to volatilization compared to PLBr.

There were few significant differences in inorganic N concentrations among PLSub treatments averaged across sampling dates. In 2014, PLSub1 had significantly higher average soil NO_3^--N concentrations compared to PLSub3. Average soil NH_4^+-N and total inorganic N concentrations for PLSub1 were statistically greater than that of PLSub3 in the 2015 growing season. The PLSub3 treatment might be expected to have higher N mineralization and inorganic N due to greater microbial accessibility in the three bands versus one. Maize N uptake may have possibly occurred sooner in PLSub3 because two of the PL subsurface bands were applied in closer proximity to the maize rows compared to the single band of PLSub1, 12.7-cm and 25.4-cm, respectively. Tewolde et al. (2018b) examined a field study comparing PL placed in a single “thick” or multiple “thin” subsurface bands between cotton rows. They noted that cotton tissue nutrient concentration data showed that young cotton plants 32-d after planting had greater access to PL N placed in multiple “thin” bands, which would be equivalent to PLSub3 in this experiment.

2.5 Conclusions

This study indicated that subsurface banding PL in a no-till maize system significantly decreased NH_3 volatilization compared to the traditional surface broadcast PL and was consistently similar to that of the untreated control. Increasing the frequency of subsurface PL bands between maize rows did not influence NH_3 losses compared to a single subsurface PL band. This is likely because complete closure of all injection bands preventing direct exposure of NH_3 to the atmosphere.

Mitigating NH_3 volatilization using the subsurface PL banding method promotes the conservation of N below the soil surface compared to PL surface broadcast without tillage incorporation. Ammonia emitted to the atmosphere also has the potential to be an indirect source of N_2O emissions following the deposition of NH_3 to soil (IPCC, 2006). This N conservation is beneficial for maize producers by potentially increasing NUE. The potential tradeoff could be additional N_2O emissions by increasing accessibility of C and N substrates to the soil microbial population, which facilitates nitrification and denitrification. All three PL subsurface band treatments significantly lower cumulative N_2O emissions in contrast to PL surface broadcast in 2014. In 2015, PLSub2 was the subsurface banded PL treatment that continued this trend; however, there was no benefit in applying PL in multiple subsurface bands in either year. The reduction in N_2O emissions by placing the PL in bands 8-cm below the soil surface could be caused by longer diffusion paths and residence time of N_2O in the soil solution, which may increase the opportunity for N_2O reduction to N_2 (Velthof et al., 2003; Webb et al., 2010).

Averaged across treatments, 2014 had an average N_2O flux of 87.4 ug N_2O-N m^{-2} h^{-1}, which was significantly higher than the average of 70.7 ug N_2O-N m^{-2} h^{-1} in 2015. With 2015 having nearly twice the precipitation and lower average N_2O emissions compared to 2014, it would suggest nitrification was a major contributor to N_2O emissions. In support of this hypothesis, soil NH_4^+-N concentrations for N amended plots steadily decreased while NO_3^--N concentrations increased for the first 45-d following treatment application. During this timeframe, most N_2O flux occurred and the WFPS was 74% averaged across years and treatments. Other research shows that denitrification doesn't dominate N_2O emissions until soil WFPS is greater than 80% (Braker and Conrad, 2011; Huang et al., 2014; Linn and Doran, 1984; Nömmik, 1956). Biogenic processes are largely responsible for N_2O emissions making it difficult to determine whether nitrification or denitrification was the predominant contributor of N_2O based off soil physical characteristics, nutrient parameters, and net N_2O flux alone.

Differences between N_2O emission factor values for treatments were mainly a direct reflection of the differences among cumulative N_2O emissions. Nitrous oxide emission factors were equal among the subsurface PL band treatments. Emission factors for N_2O ranged from 0.54% to 0.77% and 0.31% to 0.89% in 2014 and 2015, respectively which were below the IPCC Tier 1 N_2O default emission factor of 1% (IPCC, 2006).

Subsurface banding PL can have a positive effect on the environment by reducing direct N_2O emissions and possible indirect N_2O emissions associated with NH_3 volatilization in contrast to PL surface broadcast in a no-till maize system. Results did not consistently indicate there was a benefit in placing PL in more than one subsurface band between maize rows. Findings from this experiment and past studies suggest that future research is warranted to determine the effect PL subsurface band depth would have on N_2O emissions.

2.6 Tables and Figures

2.6.1 Tables

Table 2.1. Selected properties of the soil sampled to a depth of 10-cm prior to treatment application and poultry litter applied each year in the spring before planting (2014-2015).

Year	pH	Moisture	Total C	Total N	NH_4^+-N	NO_3^--N	Mehlich-3 P	Mehlich-3 K
Soil		g kg^{-1}			mg kg^{-1}			
19-May-14	6.43	228	14.05	1.41	0.9	25.1	43.4	215.1
28-Apr-15	6.08	222	14.26	1.31	0.4	14.1	94.7	194.4

Year	pH	Moisture	Total C	Total N	NH_4^+-N	NO_3^--N	Total P	Total K
Poultry litter[†]		g kg^{-1}						
2014	8.73	375	410	30.1	4.6	0.9	9.5	25.1
2015	6.14	156	369	33.1	2.0	1.5	8.6	34.6

[†] Values reported on wet basis.

Table 2.2. Cumulative nitrous oxide emissions and nitrous oxide emission factors for treatments in 2014 and 2015.

	Cumulative N_2O Emissions		N_2O Emission Factor[†]	
Treatment[‡]	2014	2015	2014	2015
	------------ kg N ha^{-1}	-------------	--------------- %	----------------
UTC[*]	0.95c	0.88c	-	-
Fert	2.15ab	2.48a	0.66ab	0.89a
PLBr	2.34a	2.32a	0.77a	0.80a
PLSub1	2.09b	2.00ab	0.63ab	0.62ab
PLSub2	1.92b	1.43bc	0.54b	0.31b
PLSub3	1.95b	1.92ab	0.56b	0.58ab

[†] N_2O Emission Factor = $[(N_2O\text{-}N_{\text{fertilized soil}} - N_2O\text{-}N_{\text{unfertilized soil}})/N_{\text{applied}}] * 100$.

[‡] Means within a column followed by different letters are significantly different at $P < 0.1$.

[*] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 2.3. Cumulative ammonia volatilization and ammonia emission factor for treatments in 2014 and 2015.

	Cumulative NH_3 Volatilization		NH_3 Emission Factor[†]	
Treatment[‡]	2014	2015	2014	2015
	------------ kg N ha^{-1} -------------		--------------- % ----------------	
UTC[*]	5.29c	6.10c	-	-
Fert	14.98a	15.87a	5.48a	5.44a
PLBr	8.57b	7.84b	1.82b	0.92b
PLSub1	5.26c	6.19c	-0.01c	0.05c
PLSub2	5.29c	5.94c	0.00c	-0.07c
PLSub3	4.96c	5.75c	-0.18c	-0.16c

[†] NH_3 Emission Factor = $[(NH_3\text{-}N_{\text{fertilized soil}} - NH_3\text{-}N_{\text{unfertilized soil}})/N_{\text{applied}}] * 100$.

[‡] Means within a column followed by different letters are significantly different at $P < 0.1$.

[*] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 2.4. Treatment effect on average soil ammonium, nitrate, and inorganic N concentrations at 0-10 cm depth for the 2014 and 2015 growing season.

	2014[†]			2015[‡]		
Treatments	NH_4^+-N	NO_3^--N	Inorganic N[*]	NH_4^+-N	NO_3^--N	Inorganic N
	$mg\ kg^{-1}$					
UTC	1.2b	21.2d	22.4c	0.5c	10.8c	11.2d
Fert	28.8a	62.1a	90.9a	47.0a	47.2a	94.1a
PLBr	1.9b	33.5bc	35.4b	0.9c	14.2b	15.2cd
PLSub1	6.2b	36.0b	42.2b	7.1b	14.3b	21.4b
PLSub2	4.9b	33.7bc	38.6b	3.0c	14.1b	17.1bc
PLSub3	2.9b	30.4c	33.3b	1.6c	14.0b	15.6cd

[†] 2014 and 2015 growing seasons had 23 soil sample dates each.

[‡] Means within each column followed by different letters are significantly different at $P < 0.1$.

[*] Inorganic N is the combination of NH_4^+-N and NO_3^--N.

[‡] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3inter-row subsurface bands.

2.6.2 Figures

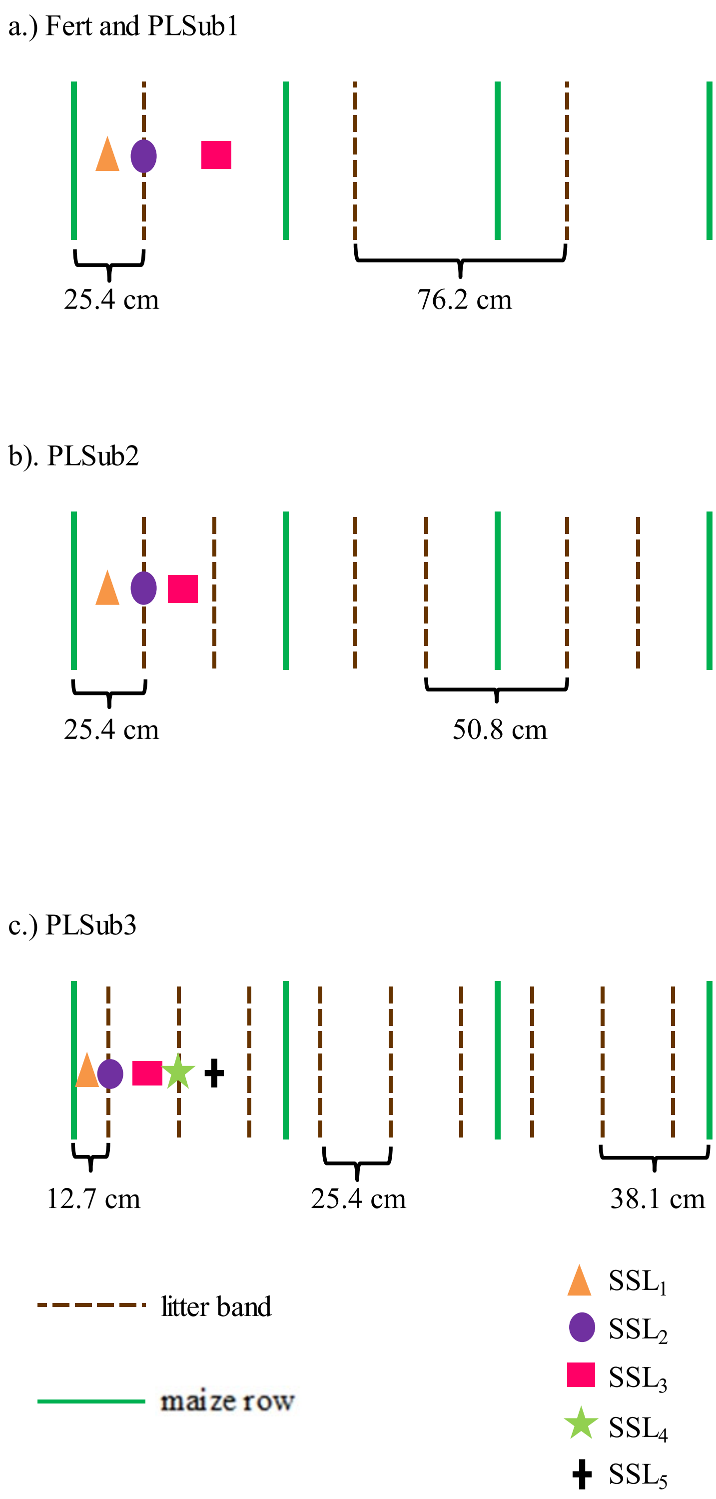

Figure 2.1. Subsurface poultry litter band placement, UAN band placement, and soil sampling schematic in relation to maize rows. Fert = urea ammonium nitrate. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands. SSL = soil sample location.

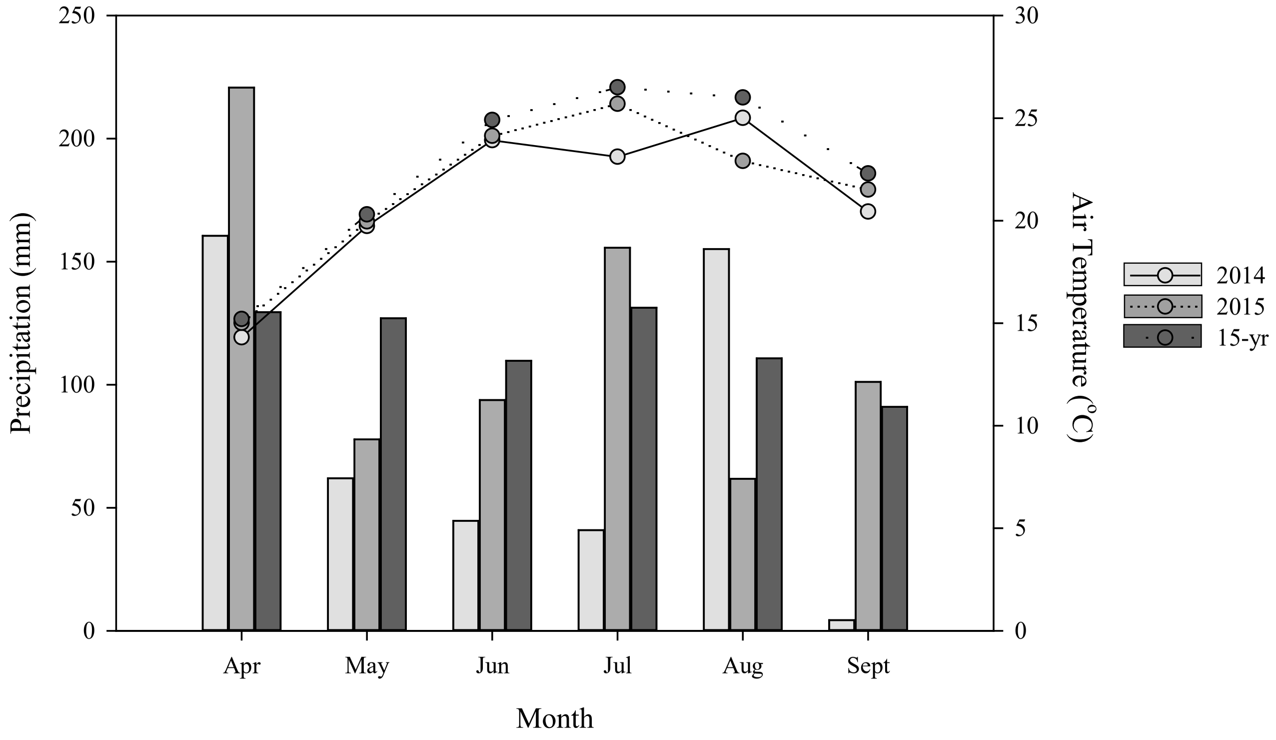

Figure 2.2. Mean monthly air temperatures (lines and points) and total monthly precipitation (bars) for study site years (2014-2015) and 15-year means (2006-2020) for Warren County, KY.

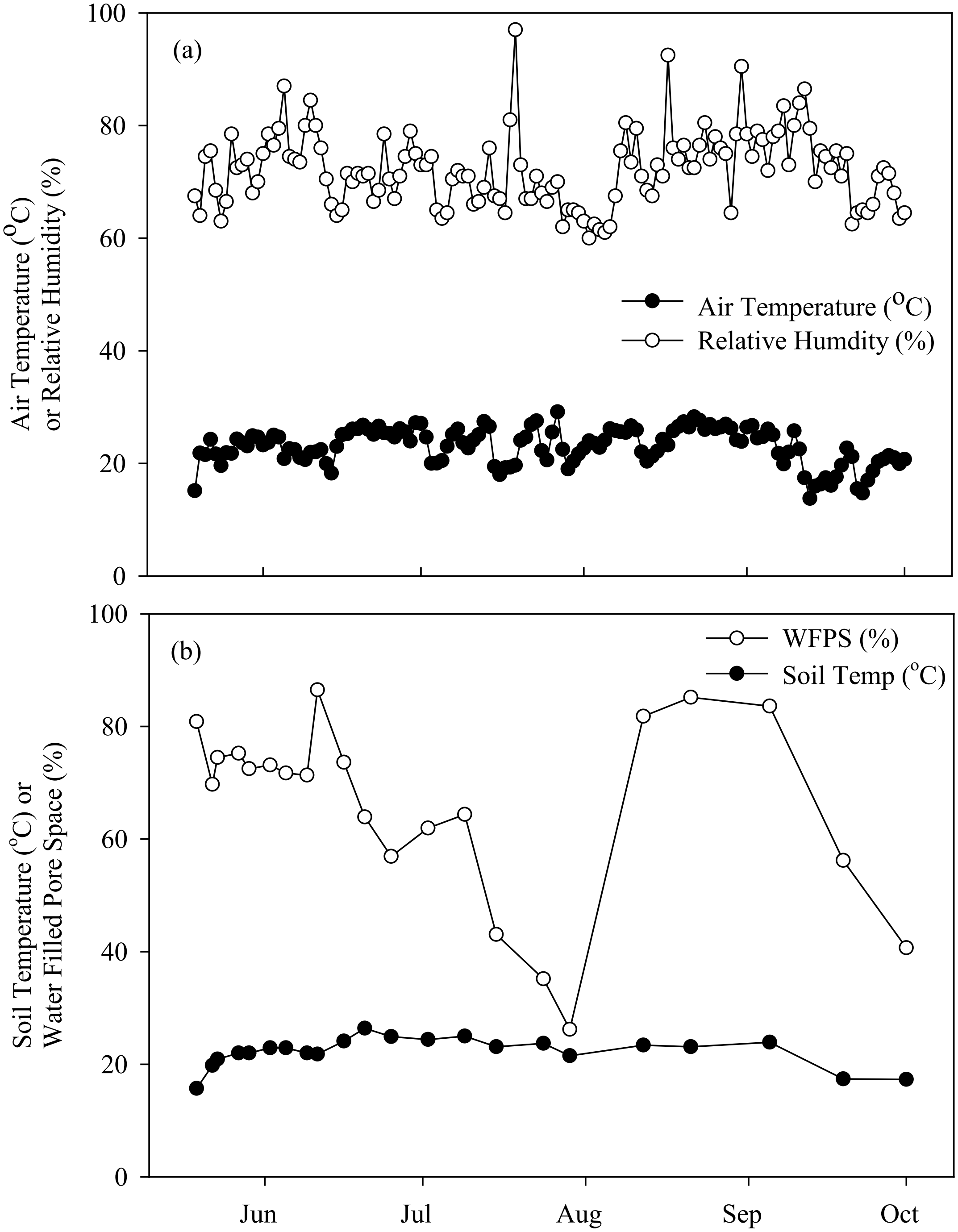

Figure 2.3. Daily mean (a) air temperature and relative humidty and (b) 5-cm depth soil temperature and water filled pore space (WFPS) measured at each sampling date during the 2014 growing season.

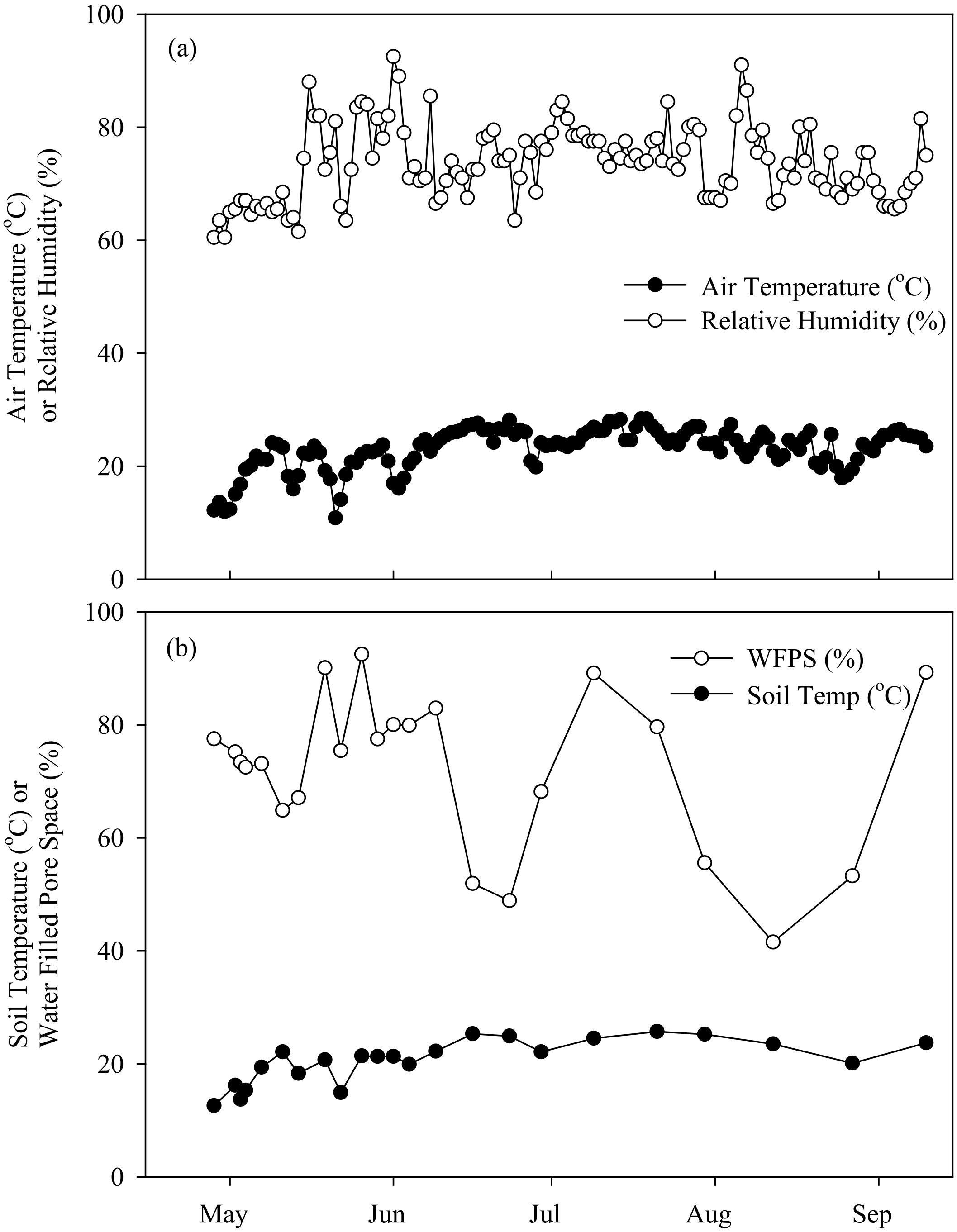

Figure 2.4. Daily mean (a) air temperature and relative humidity and (b) 5-cm depth soil temperature and water filled pore space (WFPS) measured at each sampling date during the 2015 growing season.

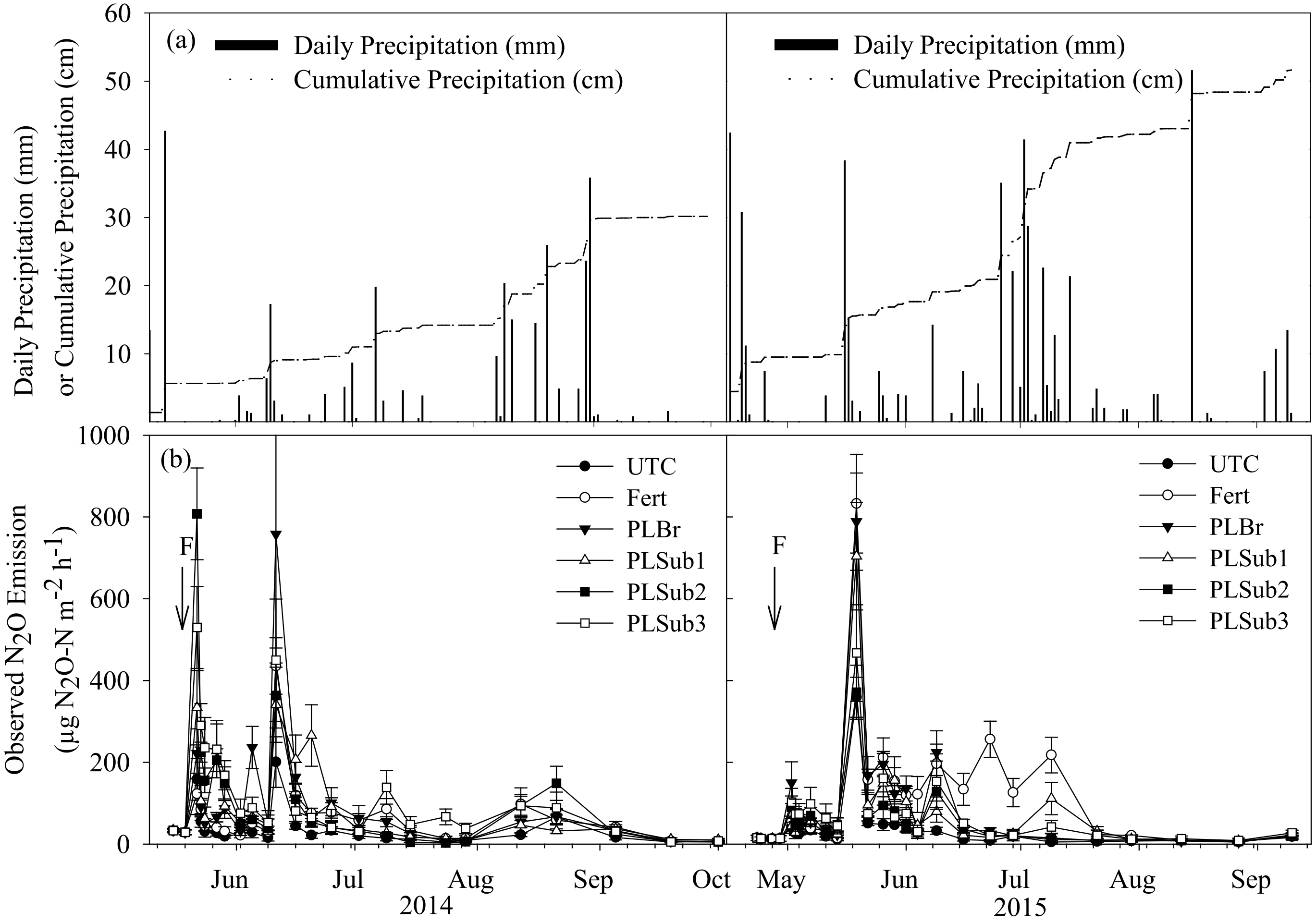

Figure 2.5. (a) Precipitation and (b) observed N_2O emissions during the 2014 and 2015 growing season. Error bars represent the standard deviation (n = 3). Arrows indicate dates of N fertilizer (F) application. UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

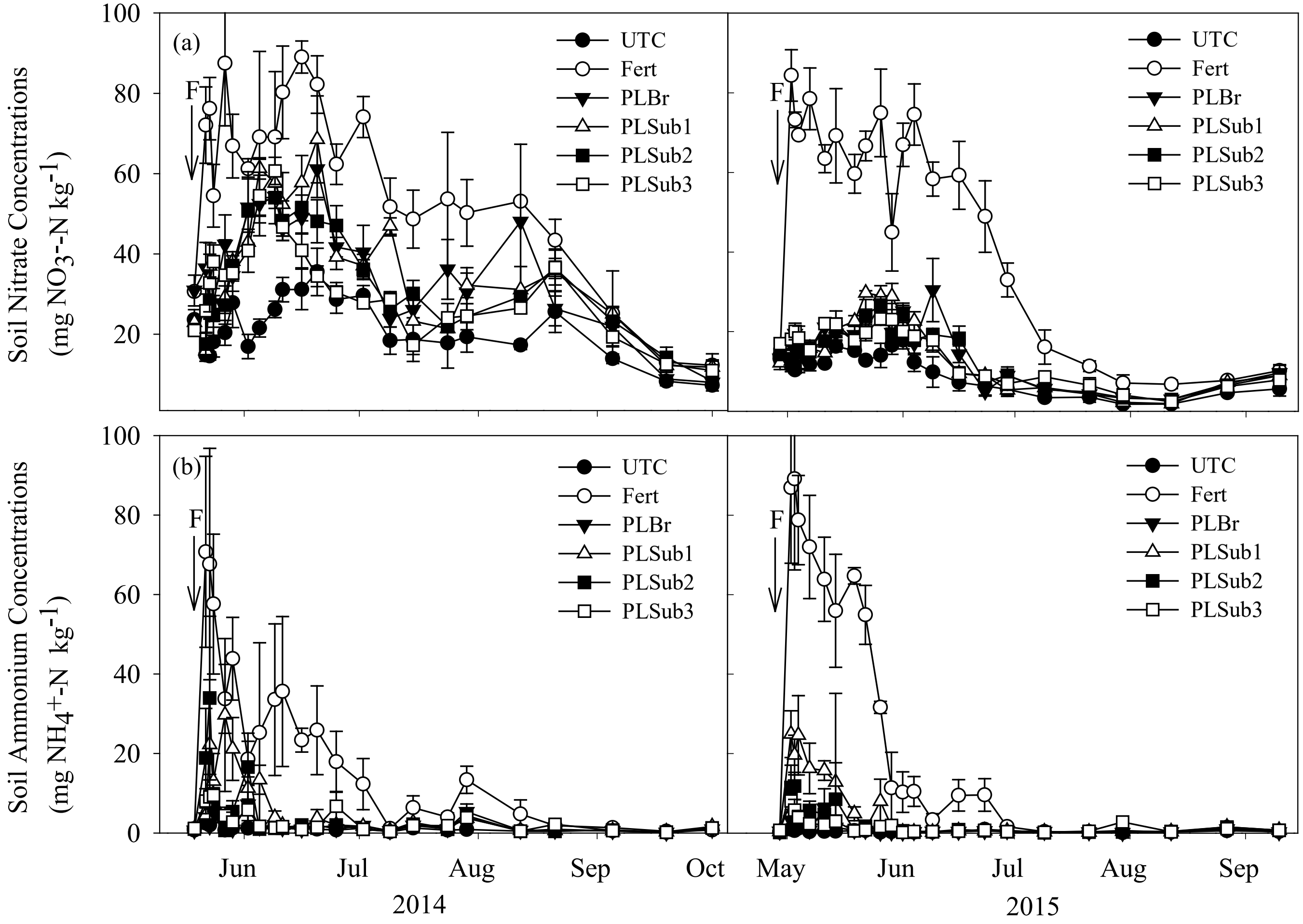

Figure 2.6. (a) Soil nitrate and (b) ammonium concentrations at the 0-10-cm depth during the growing season. Error bars represent the standard deviation (n = 3). Arrows indicate dates of N fertilizer (F) application. UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

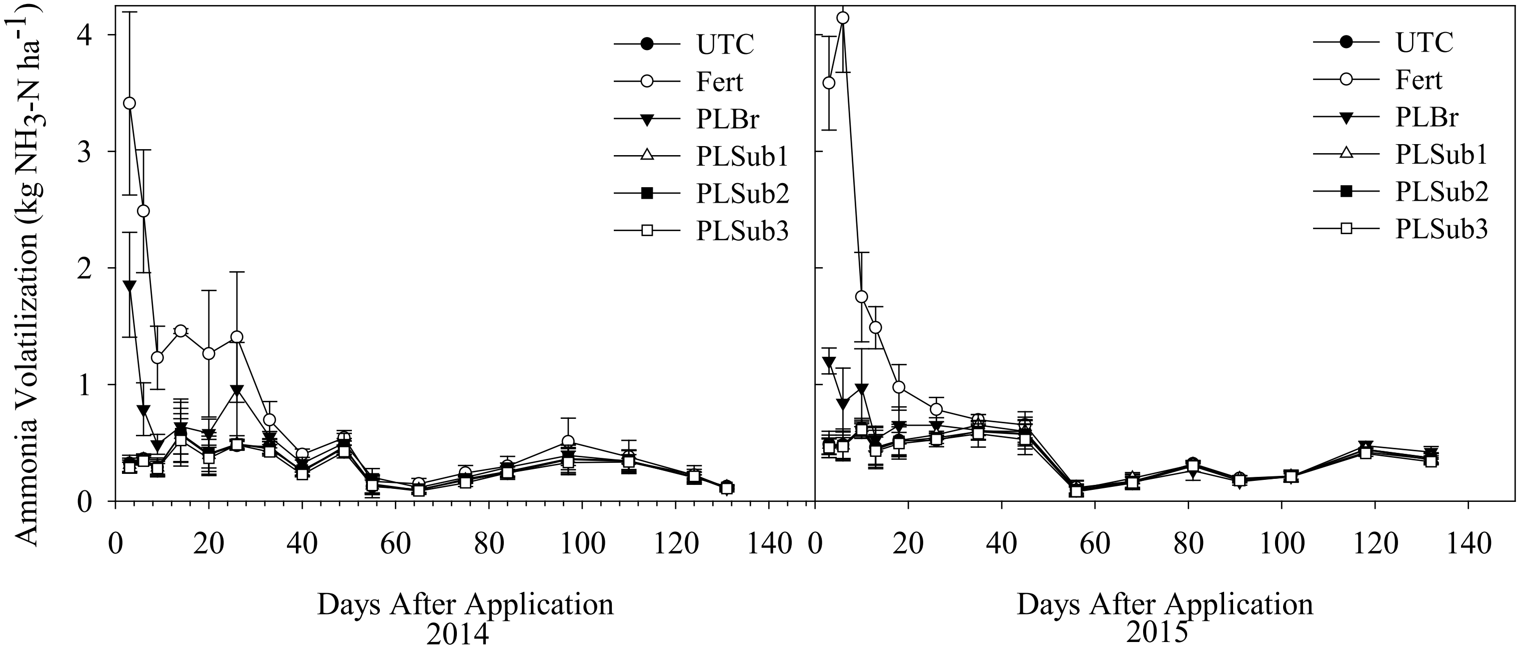

Figure 2.7. Ammonia volatilization between sampling dates for each treatment during the 2014 and 2015 growing season. Error bars represent the standard deviation (n = 3). UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

CHAPTER 3. LATERAL SPACING OF SUBSURFACE POULTRY LITTER BANDS: INFLUENCE ON MAIZE PERFORMANCE AND NITROGEN USE EFFICIENCY

3.1 Abstract

Poultry litter (PL) is traditionally applied to no-till maize (*Zea mays* L.) cropping systems by surface broadcast. Poultry litter is nutrient dense, and it has been repeatedly shown that surface applied PL nitrogen (N) and phosphorus (P) are vulnerable to losses to the atmosphere and nearby water systems. An application method was developed by USDA-Agricultural Research Service scientists for banding poultry litter (PL) below the soil surface with minimal soil disturbance to reduce ammonia (NH_3) volatilization and surface run-off. There is limited information on how this application method will affect conservation and nutrient accessibility in a no-till cropping system in Kentucky. The objectives of this study were to determine if adjusting PL lateral subsurface band placement in relation to maize rows affects nutrient use and maize yields during the growing season. A two-year field experiment was initiated May 2014 on a Crider silt loam. Treatments consisted of an untreated control (UTC), urea ammonium nitrate (UAN, 32% N) surface banded (Fert), PL surface broadcast (PLBr), and 3 subsurface banded PL treatments. The subsurface PL treatments were 1 (PLSub1), 2 (PLSub2), or 3 (PLSub3) lateral bands in the inter-maize row area. Treatments receiving N amendments were applied at the rate of 180 kg total N ha^{-1} each spring prior to maize planting. Nitrogen concentration in V4 maize aboveground dry matter was significantly higher in PLSub1 than PLSub2. Aboveground biomass yields for all PLSub treatments were greater than PLBr and similar to Fert. Subsurface PL application in 1 and 2 bands resulted in maize grain yields similar to Fert and significantly greater than PLBr and UTC when averaged across years. Few significant differences were observed in post-harvest soil sample nutrient concentrations between PLSub treatments. These results suggest that subsurface banding PL can conserve N and increase no-till maize yield over traditional surface broadcast PL. However, results also indicate that increasing the frequency of subsurface PL bands between maize rows did not clearly affect nutrient conservation or accessibility to the maize plants across the growing season.

3.2 Introduction

Fertilizer placement can influence the efficiency of a crop's nutrient recovery. It is a basic aspect of the "4R" concept of nutrient stewardship that includes using the right rate, right source, right timing, and right placement of nutrients. The poultry industry generated $1.2 billion in revenue and nearly 300 million head of broiler chickens (*Gallus gallus domesticus*) in Kentucky during 2021 (NASS, 2022a). This production generated 339,000-Mg of PL based on an average of 1.13-kg litter produced per bird (Ritz and Merka, 2013).

Poultry litter is a mixture of chicken manure, bedding material, water, unconsumed feed, and feathers that can be land-applied as a fertilizer. The use of PL as an alternative nutrient source to inorganic fertilizers has gained attention by row-crop producers in areas where poultry production is prevalent to offset the increased costs of inorganic fertilizers over the past decade. It is traditionally surface broadcast in no-till cropping systems, which can reduce the litter's effectiveness as a nutrient source due to the potential nutrient loss though volatilization and surface runoff (Kleinman and Sharpley, 2003; Pote and Meisinger, 2014; Pote et al., 2011; Sharpley, 1997; Sistani et al., 2009).

Ammonia volatilization from surface applied PL decreases the nutrient value of the manure from N loss to the atmosphere and creates an economic burden for the producer. Ammonia emitted to the atmosphere has also been linked to acidification and eutrophication from atmospheric N fallout, formation of aerosols/particulate matter adding to climate warming, and potential human health hazards (Behera et al., 2013). Eutrophication can also be enhanced from surface PL runoff by P loss to water bodies leading to increased aquatic vegetative growth, increased biological oxygen demand, fish kills, and potential loss of biodiversity (Carpenter et al., 1998; Sistani et al., 2009).

To reduce environmental issues associated with surface broadcast PL in no-till, USDA-Agricultural Research Service researchers developed an experimental implement to apply PL in bands beneath soil with minimal surface disturbance (Way et al., 2013). The implement uses a distributor and conveyor system to deliver PL from a large hopper to adjustable row trenchers that place PL into narrow bands below the soil surface while simultaneously covering the band with nearly 6-cm of soil. Research shows it is effective in reducing ammonia volatilization and nutrient losses in runoff. Numerous rainfall simulation studies show up to 90% reduction in P and other nutrient losses when PL is subsurface banded rather than surface broadcast in no-till maize, cotton (*Gossypium hirsutum* L.) and permanent pastures (Adeli et al., 2013; Sistani et al., 2009; Watts and Way, 2019; Watts et al., 2011; Watts et al., 2015b). Ammonia volatilization losses were lowered by 95% (statistically similar to untreated control plots) in no-till maize when PL was subsurface banded compared to surface application (Pote et al., 2011). Similarly, Pote and Meisinger (2014) noted NH_3 volatilization was mitigated by an average of 88% when PL was subsurface banded rather than conventional surface broadcast in maize.

Management strategies that minimize potential environmental losses should be agronomically favorable for producers. Past research shows PL subsurface banding conserves applied N and improves crop yields. Tewolde et al. (2022) compared the fertilizer value of PL applied by subsurface band and surface broadcast in maize. Subsurface banding PL had greater available N compared to surface broadcast PL (> 40% vs. < 37%). Additionally, in one year the authors noted nearly 17% more maize grain for the 1 Mg ha^{-1} profit maximizing PL rate with subsurface banded compared to surface broadcast. Maize grain yields were increased by 45% on average in a study by Ashworth and Nieman (2022) when PL at the same N rate was subsurface banded rather than surface broadcast and maize silage yields were also improved by 30%.

In a cotton study by Tewolde et al. (2009), lint yield increased from 984 kg ha^{-1} for PL surface broadcast to 1052 kg ha^{-1} for PL subsurface banded at an application rate of 6.7 mg ha^{-1}. The authors suggested PL surface broadcast application rates can be reduced by 30% when subsurface banded to produce equivalent cotton lint yields. Tewolde et al. (2018a) compared 30-cm and 102-cm subsurface PL band spacing in cotton and found the 30-cm spacing had greater cotton aboveground biomass and lint yield in the second year of a 3-yr study. The authors attributed this finding to greater early season nutrient accessibility in the 30-cm spaced PL subsurface bands. Tewolde et al. (2013b) also investigated nutrient distribution between 102-cm spaced subsurface PL bands 29 days following the second year of application and found P distribution to be concentrated near PL bands. Tewolde et al. (2018a) had reported subsurface banding PL had greater soil P and K concentrations compared to surface applied PL; no consistent differences in soil nutrient accumulation were observed between 30-cm and 102-cm spacing of subsurface PL bands in cotton. Poffenbarger et al. (2015) showed that mineral N remained within 10-cm of subsurface banded pelletized PL throughout the growing season of maize following winter cover crops.

Past research demonstrated subsurface banding of PL can improve nutrient use compared to traditional surface broadcast PL application in no-till systems such as maize, cotton, and forages. However, at the onset of this project there was no information about the effect that increasing the number of subsurface PL bands between maize rows could have on no-till maize performance and nutrient use. The objective of this research was to determine if decreasing the PL subsurface band lateral spacing could increase the ability of the no-till maize to recover nutrients for improved growth and yield during the growing season.

3.3 Materials and Methods

3.3.1 Site Description

A field plot study (2014-2015) was conducted in Bowling Green, KY, (36°55’52” N; 86°28’12” W; altitude 167-m) at the Western Kentucky University Agriculture & Research Education Center. The region has a warm temperate climate with typical annual precipitation of 127-cm and mean temperature of 15.1°C. Weather data was collected throughout the growing seasons from a nearby Kentucky Mesonet weather station located within 30-m of the study (Mesonet, 2023). The site was on a Crider silt loam soil (Fine-silty, mixed, active, mesic Typic Paleudalfs) with 8.2% sand, 69.9% silt, and 21.9% clay as analyzed by hydrometer method (Gee and Or, 2002). The plot area had previously been cropped in a no-till maize/wheat (*Triticum aestivum* L.)/soybean [*Glycine max* (L.) Merr.] rotation for at least 8-yr.

3.3.2 Experiment Design and Treatment Establishment

The experiment design was a randomized complete block with three replicates in a no-till maize system. The study site in the second year was moved to an adjacent portion of the field to reduce residual effects of the PL. Experimental units were 6.1-m by 9.1-m to accommodate 8 rows of no-till maize at 76-cm spacing. Six treatments consisted of an untreated no N control (UTC), urea ammonium nitrate (UAN, 32% N), surface banded (Fert), PL surface broadcast (PLBr), and 3 subsurface banded PL treatments. Treatments received N at a preplant of 180-kg total N ha^{-1} on 21 May 2014 and 1 May 2015. This N application rate equated to 5.96 and 5.41 Mg PL ha^{-1} for 2014 and 2015, respectively, based on the TN content of the litter (Table 3.1).

The Fert treatment was surface banded 25-cm from maize rows using a calibrated tractor power take-off-driven boom sprayer (T-30G; Bellspray Inc., Opelousas, LA). The sprayer was equiped with flat fan spray nozzle tips (TP8006-VS; TeeJet Technology, Glendale Heights, IL) turned 90° so the spray pattern was perpendicular to the spray boom. Additionally, the Fert treatment received supplemental P and K fertilization (surface broadcast) to match that of the PL treatments; 57 kg P ha^{-1} and 150 kg K ha^{-1} in 2014 and 47 kg P ha^{-1} and 187 kg K ha^{-1} in 2015.

The subsurface banded PL treatments were 1 (PLSub1), 2 (PLSub2), and 3 (PLSub3) lateral PL bands in the inter-maize row area (Figure 3.1). Each subsurface PL band supplied 100%, 50%, or 33.33% of the total N rate for PLSub1, PLSub2, or PLSub3, respectively. The PLSub1 treatment had 76-cm lateral spacing which resulted in a single PL band offset 25-cm from each maize row. The PLSub2 treatment had alternating 25-cm and 51-cm lateral spacing resulting in two subsurface PL bands offset 25-cm on both sides of each maize row. The PLSub3 treatment had lateral spacing of 25-cm which resulted in two inter-row PL subsurface bands offset 13-cm on both sides of each maize row and one PL subsurface band offset 38-cm from maize rows. The PLSub treatments were applied using an experimental tractor-mounted PL applicator implement (Way et al., 2013) that placed PL in trenches that were approximately 4-cm wide and 8-cm below the soil surface. The applicator was calibrated by adjusting the speed of the delivery conveyors, the height of the conveyor flow gates, and tractor ground speed. To reduce treatment differences from compaction, the tractor and PL loaded implement was driven over each plot an equal number of passes.

Maize was planted on 21 May 2014 and 1 May 2015 following treatment application at a seeding rate of 78,500 seeds ha^{-1} and 5.7-cm depth using a four-row no-till planter (7200 MaxEmerge 2; Deere & Company, Moline, IL). The maize hybrid seed for both growing seasons was NK N70J-4011 RR/*Bt* (Syngenta, Basel, Switzerland) and has a maturity rating of 112 days. In-season weed control consisted of atrazine 4L at 2.2 kg a.i. ha^{-1} and 41% glyphosate at 1.7 kg a.i. ha^{-1} applied with a CO_2 pressurized backpack sprayer (T4; Bellspray Inc., Opelousas, LA) equiped with flat fan spray nozzles (TP8002-VS; TeeJet Technology, Glendale Heights, IL).

3.3.3 Poultry Litter

Poultry litter used in this experiment was acquired from broiler production facilities in South Central Kentucky and nutrient content was determined on a wet basis prior to treatment application. Initially, plans were to use PL from the same broiler facility. However, in 2015 the moisture content of the original broiler producer's PL was nearly greater than 40%. This created an issue with the experimental subsurface PL banding implement accurately applying treatments due to clogging problems with the conveyor system when moisture contents exceed 35%, as noted by Way et al. (2013). Consequently, the PL used in 2015 came from another local broiler facility that had been stored in a dry stack shed since fall 2014. In 2014, no issues were experienced with accurate calibration of the PL subsurface banding implement despite a 37.5% moisture content.

Moisture content of the PL was determined by drying 20-g as-collected PL at 110°C for 24-hr, following procedures outlined in Hoskins et al. (2003). Poultry litter pH was measured in a 1:5 litter/water mixture using a digital pH meter (Orion 3 STAR pH meter and ROSS Ultra pH/ATC probe; Thermo Scientific, Beverly, MA). Microwave assisted acid digestion (U.S. EPA, 2007) was used to analyze P and K. In this method, 0.5-g PL was mixed with 9-mL HNO_3 and 3-mL HCl in microwave digestion vessels and predigested in a fume hood for 60-min. The vessels were then placed in a MARS5 microwave (CEM Corp., Matthews, NC) to ramp the sample mixture up to 175°C over 6.5-min and then held at 175°C for an additional 12-min. The digested sample mixture was filtered through quantitative grade filter paper (Q2, Fisher Scientific, Hampton, NH) before P and K analysis by an inductively coupled plasma optical emission spectrophotometer (ICP-OES) (Vista-Pro; Varian Inc, Palo Alto, CA). An adapted version of Keeney and Nelson (1996) was used to determine NH_4^+-N and NO_3^--N in the PL. Briefly, PL was extracted with 2 *M* KCl using 2-g as-collected PL in a 1:30 PL/extractant ratio, shaken at 150-rpm for 20 min, filtered through quantitative grade filter paper, and diluted 100-fold. The diluted sample extracts were analyzed on a Lachat QuikChem 8000 FIA+ flow injection instrument (Hach, Loveland, CO) using QuikChem methods 10-107-04-1-A and 12-107-06-2-A for NO_3^--N and NH_4^+-N, respectively. A Vario Max CN analyzer (Elementar Americas Inc, Mt. Laurel, NJ) was used to determine total N (TN) and total C (TC) in the as-collected PL by automated high temperature combustion and an integrated thermal conductivity detector (TCD).

3.3.4 Plant Tissue Collection and Analysis

Ten whole aboveground plant samples were collected randomly from rows 2 and 7 of every plot on 16 June 2014 and 29 May 2015 when maize was at the V4 growth stage when maize has 4 collared leaves to determine early season nutrient concentration. Maize ear-leaf samples were collected on 15 July 2014 and 29 June 2015 by removing the ear-leaf at tasseling from 10 maize plants in rows 2 and 7 from each plot and combined to make a composite sample. At the R6 growth stage when maize has reached physiological maturity, whole plants above the soil surface were harvested on 22 August 2014 and 12 August 2015 to determine aboveground plant nutrient uptake. All plants within a randomly selected 6-m length from rows 3 and 6 in each plot were cut at soil level, weighed, and all plant material was shredded with a wood chipper (Modern Tool and Die Company, Cleveland, OH). Following shredding, all plant material was homogeneously mixed by hand and subsamples taken for analysis. Maize grain was hand-harvested on 30 September 2014 and 9 September 2015 from a randomly selected 1.5-m by 3-m section from the center rows of each plot. Grain moisture was recorded at harvest with a portable moisture tester (MT-Pro; Agritronix, Streetsboro, OH).

All plant samples were dried at 65°C for at least 72-hr using a forced air oven (FX28-2; Shel Lab, Cornelius, OR). They were then processed with a grinder mill (Wiley Mill Model 4; Thomas Scientific, Swedesboro, NJ) to pass a 2-mm mesh sieve prior to laboratory analysis. One gram subsamples of all plant tissues were analyzed for TN and TC using a Vario Max CN analyzer by high temperature combustion coupled with TCD. A dry ash and acid extraction procedure (Miller, 1998) was used to analyze tissue samples for total P (TP) and total K (TK). Maize tissue subsamples of 0.2-g were ashed in a muffle furnace (Isotemp 10-650-126; Fisher Scientific, Hampton, NH) at 500°C for 4-h and then extracted with 1-mL 6 M HCl for 1-h followed by 40-mL acid solution (0.0125 M H_2SO_4 and 0.05 M HCl) for 1-h. Sample extracts were then filtered through quantitative grade filter paper and analyzed for TP and TK using ICP-OES.

Fertilizer and plant based nitrogen use efficiency (NUE) indicies are often used to express the effectiveness of maize to take up and convert amended N to affect plant parameters such as aboveground biomass, grain, or N content. The following NUE indicies for this study were based on calculations from Woli et al. (2016).

Nitrogen recovery efficiency (NRE) is the ability of aboveground maize to take up fertilizer N applied:

$$\text{NRE } (\Delta \text{ kg kg}^{-1}) = (\text{PNU}_{\text{N}} - \text{PNU}_{\text{UTC}})/\text{N rate}$$

where PNU_{N} is the plant N uptake from treatments receiving N fertilizer and PNU_{UTC} is the plant N uptake from the untreated check without N fertlizer.

Agronomic efficiency (AE) is the contribution of fertilizer N to the increase in maize grain yield (GY):

$$\text{AE } (\Delta \text{ kg kg}^{-1}) = (\text{GY}_{\text{N}} - \text{GY}_{\text{UTC}})/\text{N rate}$$

where GY_{N} is the grain yield from treatments receiving N fertilizer and GY_{UTC} is the grain yield from the untreated check without N fertilizer.

Grain harvest index (GHI) is expressed as the percentage of the total plant biomass (TPB) that is contained in the GY:

$$\text{GHI } (\%) = (\text{GY}/\text{TPB}) \times 100$$

3.3.5 Soil Sample Collection and Analysis

Background soil samples from a 2.54-cm inside diameter soil probe to a depth of 10-cm were randomly collected throughout each plot prior to treatment application on 19 May 2014 and 28 April 2015. Soil cores taken at post-harvest sampling dates of 1 October 2014 and 10 September 2015 were separated into depths of 0-10, 10-20, and 20-30-cm. Plots with UTC and PLBr treatments were sampled randomly across the plot area excluding the border rows at post-harvest. Plots receiving banded treatments (Fert and PLSub) had a nested soil sampling scheme that produced 3, 3, or 5 subsets for 1, 2, or 3 band treated plots, respectively (Figure 3.1). The Fert and PLSub1 plots had 3 soil cores taken; 1.) 25-cm from the maize in the fertilizer band, 2.) in the middle of the 25-cm spacing between the maize row and fertilzer band, and 3.) in the middle of the 51-cm spacing between the maize row and fertlizer band. The PLSub2 treatment had 3 soil cores taken; 1.) in the middle of the distance between the maize row and nearest PL band, 2.) in the PL band, and 3.) in the middle of the distance between PL bands which was approximately 38-cm from maize rows. The PLSub3 plots had 5 soil cores taken; 1.) in the middle of the distance between the maize row and nearest PL band, 2.) in the nearest PL band from the maize row, 3.) in the middle of the distance between the nearest and furthest PL band from maize rows, 4.) in the furthest PL band from the maize rows, and 5.) an additional core similar to core 3 however on the opposite of the PL band in core 4.

The nested samples were collected in three random locations within plots, composited based on location sampled between the inter-row area, analyzed as individual samples, and nutrient concentrations calculated for each plot based on a weighted average of individual subsamples to represent the inter-row maize area. The following equations demonstrate how the nutrient concentration averages were calculated for each banding treatment and subscripts represent soil sample location (SSL) within the inter-row area for each treatment as previously mentioned.

Fert and PLSub1

$$\text{Plot}_{\text{AVG}} = (\text{SSL}_1 + \text{SSL}_2 + \text{SSL}_3) / 3$$

PLSub2

$$\text{Plot}_{\text{AVG}} = (2\text{SSL}_1 + 2\text{SSL}_2 + \text{SSL}_3) / 5$$

PLSub3

$$\text{Plot}_{\text{AVG}} = (2\text{SSL}_1 + 2\text{SSL}_2 + \text{SSL}_3 + \text{SSL}_4 + \text{SSL}_5) / 7$$

Composited soil samples from background and post-harvest sampling dates were placed in zip seals bags, homogenously mixed manually, and half the sample transferred to another zip seal bag to be stored at 4°C for inorganic N determination. The remainder of the soil sample was air dried, ground with a soil crusher (Dynacrush; Custom Laboratory Equipment Inc., Orange City, FL), and sieved to pass a 2-mm mesh screen. These samples were analyzed for soil pH solution by a pH meter and electrode using a 1:1 soil/0.01 *M* $CaCl_2$ ratio mixed for 10-min and after a 10-min waiting period. Total N and C were obtained using 1-g of air-dried sample measured by automated dry combustion with a VarioMax CN analyzer. Extractable P and K were assessed using Mehlich-3 (M3) extractant and 2-g soil in a 1:10 soil/M3 ratio, shaken for 30-min at 150 rpm, and filtered through quanititative grade filter before analysis using ICP-OES (Mehlich, 1984). As-collected soil samples stored at 4ºC were analyzed for NO_3^--N and NH_4^+-N by flow-injection analysis after extraction with 2 *M* KCl (Keeney and Nelson, 1996). Briefly, soil was extracted with a 1:10 soil/2 *M* KCl extraction ratio, shaken at 150 rpm for 20-min, filtered through quantitative grade filter paper, and analyzed by flow injection analysis with QuikChem methods 10-107-04-1-A and 12-107-06-2-A for NO_3^--N and NH_4^+-N, respectively.

3.3.6 Statistical Analysis

Data analysis among treatments was subjected to a generalized linear mixed model analysis of variance (SAS Institute Inc., 2013). The Kenward-Rodger method was used to calculate degrees of freedom. Data for each year were further analyzed individually if there was a significant year and treatment interaction ($P < 0.1$). Means were separated according to Fisher's Protected LSD at $\alpha = 0.1$ to make statistical comparisons.

3.4 Results and Discussion

3.4.1 Environmental Factors

Total precipitation from April to September, 2014 was 46.8-cm, which was much lower than the 71-cm in 2015 and 70-cm for the 15-yr means for Warren County, KY. (Figure 3.2). Maize agronomic performance did not greatly differ between growing seasons despite dramatic differences in total monthly precipitation in July and August for 2014 and 2015. Total precipitation for July was 280% greater in 2015 compared to the same month in 2014. Conversely, August 2014 had total precipitation that was 150% higher than August 2015. Maize water use in KY is typically 127-mm for each month during July and August (Lee et al., 2022; Rasnake et al., 2000). A deficit of 86-mm in July 2014 and 65-mm in August 2015 was observed. The later planting date in 2014 shifted the reproductive growth stages later in July compared to 2015, which mitigated the effect of water deficiency on maize yield.

Monthly mean air temperatures ranged from 14.3ºC to 25.7ºC with an average of 23.0ºC in 2014 and 23.4ºC in 2015. The 2014 and 2015 growing season were cooler than the 15-yr means for Warren County, KY (National Centers for Environmental Information, 2022). Average daily air temperatures were generally cooler for the first 40 days after planting in 2015 compared to 2014 (Figure 3.3) which resulted in 2.3% fewer growing degree days (GDD) 115 days following planting. Overall, air temperatures were mild across both growing seasons without extended periods of excessive heat stress, which may have minimized the water deficiency observed in July 2014 and August 2015.

3.4.2 Maize V4 Aboveground Dry Matter and Ear-leaf Nutrient Concentrations

Year by treatment interactions of maize V4 aboveground dry matter and ear-leaf nutrient concentrations were not significant, so the data presented is averaged across 2014 and 2015 (Table 3.2). As expected, fertilizer treatment had a significant effect on N, P, and K concentrations in V4 aboveground dry matter and ear-leaf samples. The PLSub1 and PLSub3 treatments had similar V4 aboveground dry matter N and K values to Fert and PLBr while higher than UTC. Maize V4 aboveground dry matter nutrient concentrations were similar between PLBr and PLSub applications; however, there were significant differences among the PLSub treatments. The PLSub1 had significantly greater V4 aboveground dry matter N concentrations compared to PLSub2. This was surprising because these two treatments were equally spaced from the maize row. However, PLSub2 is offset on both sides of the maize row compared to only one side for PLSub1. This could potentially be due to the higher concentration of N in the single band of PLSub1 moving laterally towards the maize row at a higher concentration compared to that of PLSub2. At the V4 growth stage, maize has already developed the nodal roots and is just starting to develop the secondary root system. This may explain the inefficiency of the V4 plants to utilize N from lower N concentrations moving laterally from PLSub2 bands compared to higher concentrations of N in PLSub1. Tewolde et al. (2013b) investigated the lateral movement of soil nutrients in a silt loam from subsurface PL bands 42-d after application and noted that the presence of the band was not clearly detected based on the concentration of TN taken at 5-cm intervals away from the PL subsurface band. The authors explained this was likely a combination of the mobility and natural variability of N in the soil. The V4 tissue samples in this study were taken 27-d after treatment application, which may not had as much N lateral diffusion from the PL band compared to that of Tewolde et al. (2013b).

PLSub3 had significantly higher V4 aboveground dry matter K than PLSub2 which can be explained by PLSub3 having the lowest offset spacing from the maize row allowing greater K access to the young root system of the V4 maize plants. There was no significant difference in V4 aboveground dry matter P concentrations between PL treatments and UTC. This is likely attributed to background soil samples in 2014 and 2015 having soil test P values (Table 3.1) in the high category for maize production according to the University of Kentucky, which recommends that no additional P fertilization is needed to achieve optimal yields (Ritchey and McGrath, 2020). Additionally, no differences were observed in V4 aboveground dry matter P concentrations between PLBr and PLSub treatments. Schwab et al. (2006) conducted a research study to determine the effect of P placement on crop growth. At one of two sites that no-till V6 maize P uptake was not significantly different between broadcast and subsurface banded inorganic P fertilizer despite initial soil test P values in the low range for recommendations. Schwab et al. (2006) concluded that higher early season P recovery did not consistently result in greater grain yield, which agrees with other literature (Barber, 1980; Mallarino et al., 1999).

Maize ear-leaf N and K concentrations were significantly lower for UTC compared to all other treatments that received soil amendments. The University of Kentucky's macronutrient sufficiency range for maize ear leaf samples would suggest the UTC had possible N and/or K deficiencies that may have affected maize yields (Schwab et al., 2007). Background soil samples (Table 3.1) for both growing seasons indicate soil K was adequate for the expected yields according to University of Kentucky recommendations (Grove and Ritchey, 2022). Grove and Ritchey (2022) explained N is often the limiting nutrient for maize production because organic N mineralization in KY soil is often too low and unpredictable to supply available N to maize crops without supplement N fertilization for optimal maize yields.

In this experiment there were no significant differences in ear-leaf N, P, and K concentrations between the PL treatments. Tewolde et al. (2018b) noted similar results for cotton leaf P and K concentrations sampled in July when comparing PL that was applied in narrow surface bands, narrow subsurface bands, and wide subsurface bands. However, cotton leaf N concentrations were significantly increased with the wide subsurface bands compared to the other two PL treatments. They attributed this increase to a greater conservation of N in a single "thick" band of PL for each row of cotton versus multiple "thin" bands. In this study, all PL treatments had significantly lower ear-leaf N concentrations than Fert, which is likely due to basing the application rate on 100% availability of N in the PL, which may have resulted in insufficient N supply at this point of the growing season. The University of Kentucky recommends PL application rates based on assuming 45 to 60% of the N will be available to the maize crop dependent on when the PL is applied and incorporated (Rasnake et al., 2000). Other studies have reported PL N availability to range between 30 and 44% based on application method and timing in a maize cropping system (Tewolde et al., 2013a; Tewolde et al., 2022). The availability of N in PL depends on an extensive range of factors including PL composition, application timing, application method, and N mineralization rates which can be influenced by soil pH, moisture, temperature, and aeration.

3.4.3 Maize R6 Aboveground Dry Matter Yield and Nutrient Uptake

Maize R6 aboveground dry matter and nutrient uptake values were averaged over the 2014 and 2015 because there was no significant year by treatment interactions ($P \leq 0.1$) (Table 3.3). Treatments significantly affected R6 biomass nutrient concentrations, biomass nutrient uptake, and biomass yield. Concentrations of N and K were positively influenced by Fert and PL addition compared to the UTC. PLSub1 had 25% greater R6 biomass N uptake than PLBr. This could be due to greater N conservation when PL is applied in a single concentrated band for every maize row compared to surface broadcast, as was the case noted previously by Tewolde et al. (2018b).

PLSub1 had the highest NRE of all PL treatments (Table 3.4). On average, PLSub treatments increased NRE by 81% compared to PLBr, and all PLSub treatments were statistically equivalent to that of Fert. Plots receiving PL had significantly lower R6 biomass N concentrations in relation to Fert, which was the same result observed with ear-leaf N concentrations (Table 3.2). Surprisingly, these results did not translate into lower R6 biomass N uptake and biomass yield of PLSub treatments compared to Fert.

Subsurface banding PL rather than surface broadcast resulted in a significant increase in R6 biomass yields, 13.6% on average. In agreement with these findings, a study by Adeli et al. (2012) found that subsurface banding nonpelletized PL significantly increased maize biomass yield, biomass N uptake, and NUE by 9%, 23%, and 56%, respectively, compared to that of surface broadcast PL. Tewolde et al. (2018a) reported similar results in cotton, where subsurface application of PL improved aboveground dry weight data by 25% in one of three years when PL was applied. Other studies cited no significant differences between surface and subsurface application of PL on maize biomass yields or biomass N uptake (Ashworth and Nieman, 2022; Ashworth et al., 2020b; Poffenbarger et al., 2015; Simmons et al., 2016).

Numerous factors can affect the availability of N derived from PL amendments to cropping systems including PL composition, application timing, climate, and soil biogeochemical properties. There were very few differences in R6 biomass nutrient uptake and yield between PLSub treatments. Maize biomass P uptake was significantly greater for PLSub2 than for PLSub3, which is surprising because two bands of PLSub3 were in closer proximity to the maize row than PLSub2. It is possible the third band of PLSub3, containing a third of the total P in the treatment, was located half the distance between maize rows and was underutilized by the maize.

The R6 biomass nutrient uptake and biomass yield suggests that PL subsurface banding can result in greater efficiency to utilize nutrients and increase biomass yield compared to traditional surface broadcasting of PL. However, the data indicated there was no consistent benefit in applying multiple subsurface bands between maize rows.

3.4.4 Maize Grain Yield and Nutrient Uptake

This study showed very few differences in maize grain nutrient concentration among treatments (Table 3.5). Maize grain P and K concentrations were similar among all treatments, but N concentrations were as follows: Fert>PLSub3=PLSub2=PLSub1=PLBr>UTC. As expected, treatments receiving soil amendments had significantly greater grain yield and N, P, and K uptake than UTC. PLSub1 and PLSub2 had higher grain N uptake and yield compared to PLBr, which indicates these treatments were more efficient at N utilization. These results agree with research conducted by Simmons et al. (2016) that reported increased maize grain yield and biomass N uptake when PL was subsurface banded as opposed to surface broadcast in a no-till system. This observation was only significant in one year, however Simmons et al. (2016) noted maize germination in another year was impeded by 10% in PL subsurface banded plots due to maize rows planted directly in the PL subsurface band. This germination issue has also been documented by Tewolde et al. (2022) in maize and Lin et al. (2017) in cotton. Additional studies have also shown that maize grain yields increased when PL was subsurface banded rather than surface applied and credited this increase to improved N conservation and accessibility of N to maize root systems

(Ashworth and Nieman, 2022; Ashworth et al., 2020b; Pote et al., 2011; Tewolde et al., 2022).

Agronomic efficiency increased by 40 and 64% for PLSub1 and PLSub2, respectively, compared to PLBr (Table 3.4). This demonstrates how much more efficiently N is being utilized in the production of maize grain when comparing PL application methods. The Fert treatment had GHI values that were statistically greater than UTC, PLSub1, and PLSub3. No differences were observed for GHI between most treatments receiving PL and the UTC, which may suggest that GHI was not an adequate indicator in distinguishing N efficiencies between PL treatments in this study. PLSub2 did significantly improve maize grain yield over PLSub3 (Table 3.5), which agrees with findings by Ashworth and Nieman (2022) that PL subsurface banded 25.4-cm away from the maize row had maize grain yields significantly greater than PL subsurface banded 13-cm away from the maize row. The 25.4-cm and 13-cm spacing is similar band spacing from the maize row found in PLSub2 and PLSub3 of our study, respectively, however their treatments were only one subsurface band for each maize row. They speculated that P and K in PL at the wider spacing became more plant available later in the growing season to meet requirements for maize grain production. However, this was not clearly reflected in the grain nutrient concentration and nutrient uptake data for the current study.

3.4.5 Treatment Effects on Measured Soil Properties

Significant treatment effects on residual soil NO_3^--N and total inorganic N at 0-10-cm depth were observed at the end of the 2014 growing season however there were no significant differences among treatments receiving a soil amendment (Table 3.6). Post-harvest residual soil NO_3^--N and total inorganic N at 0-10-cm depth were all below background soil concentrations (Table 3.1) for both growing seasons, which would indicate that N rates were well synchronized with maize requirements. Overall, there were more treatment differences following the 2015 growing season, which may have been attributed to having less background soil NH_4^+-N and NO_3^--N than 2014 (Table 3.1). The 2014 plot area was established following a growing season of maize that had been fertilized with 224 kg N ha^{-1} which could have resulted in residual N carryover. PLSub treatments did have significantly more post-harvest soil NH_4^+-N at 0-10-cm depth compared to PLBr in 2015. This trend was also observed in 2014 although differences were not significant (Table 3.6). Late season N mineralization of PLSub could result in the accumulation of NH_4^+-N due to the decrease in maize N demand late in the growing season. Even though it isn't statistically significant, a closer evaluation of post-harvest soil NO_3^--N at the 10-20-cm and 20-30-cm depths reveal that Fert and PLSub treatments had numerically elevated values compared to PLBr. This may suggest leaching of excess N through the soil profile, likely due to the placement of PL nearly 8-cm below the soil surface before planting for the PLSub treatments. A study by Adeli et al. (2012) comparing surface and subsurface applied PL in maize resulted in elevated soil NO_3^--N values of inorganic N fertilizer and subsurface banded PL at deeper soil core depths than surface applied PL at the end of one growing season. They attributed this potential loss of N to increased rainfall that growing season, which leached NO_3^--N below the maize root zone. Although post-harvest soil NO_3^--N results suggest potential loss of N through leaching in PLSub treatments, maize performance was not negatively affected as previously noted with R6 biomass N uptake, R6 biomass yield, maize grain N uptake, and maize grain yield data (Table 3.3 and Table 3.5).

In 2014 and 2015 there were very few significant differences in post-harvest soil TN among treatments at all three sampling depths (Table 3.7). Soil TN at the 0-10-cm was not significantly affected by N amendments and similar results have been reported by other studies (Simmons et al., 2016; Tewolde et al., 2018a). Post-harvest soil TC at 0-10-cm depth was elevated for all treatments receiving a soil amendment compared to UTC in 2014 and 2015, however, the only significant difference was in 2014 when PLSub was greater than UTC. Application of PL in 2014 was calculated to supply 2.44 Mg C ha^{-1}, which was 11.6% of the TC (21.1 Mg C ha^{-1}) initially reported in the soil prior to treatment application (Table 3.1). Based on 2014 post-harvest soil TC values at 0-10-cm depth, PLSub and PLBr increased soil TC by 7.5% and 3.3% compared to the initial background soil TC concentration, respectively. Small increases in soil TC in subsurface banded PL compared to surface applied PL have also been reported in a no-till cotton study by Tewolde et al. (2018a). They noted the slight TC increases from subsurface banding PL plots were possibly due to increased cotton and wheat cover crop biomass compared to surface applied PL.

In 2014, PLSub1 and PLSub2 significantly affected post-harvest soil M3-P with increases of 135% and 104% over that of PLBr, respectively (Table 3.7). These large discrepancies between PL treatments could likely demonstrate that the soil sampling protocol didn't accurately represent soil P status within PLSub plots. Tewolde et al. (2013b) examined nutrient distribution between bands of subsurface PL and reported soil extractable P was nearly 50 times greater within the PL band than the average of all 18 cores taken at 5-cm increments between the PL bands. For elements that aren't very mobile in the soil they concluded that the most feasible and accurate method for soil sampling PL subsurface banded areas would be to proportionally mix a soil core taken within the band and then a number of soil cores between the bands that are equal to the band spacing divided by the width of each band. According to this protocol, for accurate soil M3-P concentrations, 15, 15 (5 for 25.4-cm band spacing and 10 for 50.8-cm spacing), and 5 soil cores between PL subsurface bands should have been collected for PLSub1, PLSub2, and PLSub3 rather than 2, 2, and 3 soil cores, respectively. In 2015 there were no significant differences in post-harvest soil M3-P values between treatments. This could have been due to increased rainfall in 2015 which enhanced maize root growth and accessibility to P in the PL bands (Figure 3.2).

As expected, there were some treatment effects on post-harvest soil M3-K concentrations at 0-10-cm depth in 2014 and 2015 (Table 3.7). In 2014, PLBr and PLSub2 had significantly greater post-harvest soil M3-K concentrations compared to that of UTC. The same trend continued in 2015 post-harvest soil samples for PLBr, PLSub1, and PLSub2 having increased soil M3-K concentrations to that of UTC. Poultry litter as a nutrient source when applied based on N needs of the crop generally creates a surplus of P and K (Jn-Baptiste et al., 2012; Schomberg et al., 2009). In 2015, PLBr had 32%, and 40% greater post-harvest soil M3-K values at 0-10-cm depth than PLSub2, and PLSub3, respectively. This could be credited to PLBr having 19% less R6 aboveground biomass K uptake compared to the average of all PLSub treatments over both growing seasons (Table 3.3). The soil sampling scheme used in this study is likely a good reflection of K in the soil due to the increased mobility of K compared to P. The previously mentioned study of soil sampling following subsurface banding PL by Tewolde et al. (2013b) noted K moved 20-cm laterally from the PL band.

The frequency of subsurface PL bands between maize rows did not consistently affect soil nutrient concentrations when sampled following maize grain harvest. The protocol for soil sampling plots with subsurface PL bands may not have been adequate to distinguish differences between PLSub treatments. Tewolde et al. (2018a) also concluded that subsurface PL band spacing in no-till cotton system may not be a determining factor when considering nutrient retention in the soil.

3.5 Conclusions

This study indicated that increasing the frequency of subsurface PL bands between maize rows did not have a consistent influence on maize growth and yield. Placing PL in one concentrated subsurface band for each maize row resulted in similar nutrient concentrations of tissue samples, R6 biomass nutrient uptake, R6 biomass yield, and grain yield compared to multiple PL subsurface bands. The PLSub1 and PLSub2 treatments, on average, improved R6 biomass yields and grain yields by 2.25 and 1.15 Mg ha^{-1}, respectively, in contrast to that of PLBr and were equivalent to Fert. These findings agree with numerous studies (Adeli et al., 2012; Ashworth et al., 2020b; Pote et al., 2011; Simmons et al., 2016; Tewolde et al., 2009; Tewolde et al., 2022) that show greater crop performance from subsurface banding PL because it allows conservation of nutrients which may be lost to NH_3 volatilization and/or surface run-off when PL is surface broadcast.

Nitrogen use efficiency indices are often used to measure the ability of plants to utilize soil applied N in plant tissue components. Of the three NUE measurements in this study, only AE had a significant difference between the PLSub treatments, with PLSub2 > PLSub3. All PLSub treatments improved NRE in contrast to PLBr while only PLSub1 and PLSub2 significantly increased AE over PLBr. Improvement of these quantitative measurements generally have positive impacts on the environment by reducing the amount of N that could be potentially lost to the atmosphere, surface water bodies, and groundwater.

The spacing of subsurface PL bands had minimal impact on measured soil nutrient concentrations at post-harvest sampling dates each year. This is likely a reflection of similar aboveground biomass nutrient uptake between PLSub treatments at physiological maturity. The uptake of P at R6 was the solitary occurrence of a significant difference between PLSub treatments, with PLSub2 > PLSub3. Results from this study indicate that soil nutrient retention following maize harvest should not be a key factor when deciding which subsurface PL band spacing will be appropriate for a producer's operation.

Currently, surface broadcast application of PL is the chosen method by no-till farmers because it is a fast and relatively cheap method for applying PL. Findings from this study validate that nutrients can be conserved by subsurface banding PL and improve maize grain yields compared to traditional surface broadcast application. An extensive literature review by Maguire et al. (2011) on manure management technology states there have been many advances in manure application technology compared to surface broadcasting, however concerns remain on which application methods performs best for certain soils, manure composition, and cropping systems. Findings of this study would need support from future research investigating subsurface banded PL under different soil conditions, environments, and management practices to determine if this technology is a viable and economical alternative for Kentucky no-till maize farmers.

3.6 Tables and Figures

3.6.1 Tables

Table 3.1. Selected properties of the soil sampled to a depth of 10-cm prior to treatment application and poultry litter applied each year in the spring before planting (2014-2015).

Year	pH	Moisture	Total C	Total N	NH_4^+-N	NO_3^--N	Mehlich-3 P	Mehlich-3 K
Soil		------------ $g\ kg^{-1}$--------------			---------------------- $mg\ kg^{-1}$-------------------------			
19-May-14	6.43	228	14.05	1.41	0.9	25.1	43.4	215.1
28-Apr-15	6.08	222	14.26	1.31	0.4	14.1	94.7	194.4
Year	pH	Moisture	Total C	Total N	NH_4^+-N	NO_3^--N	Total P	Total K
Poultry litter[†]		-- $g\ kg^{-1}$ --						
2014	8.73	375	410	30.1	4.6	0.9	9.5	25.1
2015	6.14	156	369	33.1	2.0	1.5	8.6	34.6

[†] Values reported on wet basis.

Table 3.2. Maize V4 aboveground dry matter and ear-leaf nutrient (N, P, and K) concentrations pooled across 2014 and 2015.

	V4 Maize Aboveground Dry Matter			Maize Ear-Leaf		
Treatment[†]	N	P	K	N	P	K
	----------	----------	----------	g kg^{-1} ----------	----------	----------
UTC	39.6c	3.94b	39.8c	24.4c	2.83b	15.6b
Fert	44.8a	4.19a	47.4a	30.3a	2.86b	17.7a
PLBr	42.6ab	4.11ab	45.8ab	27.8b	3.00a	17.8a
PLSub1	44.9a	3.89b	46.1ab	27.8b	2.92ab	18.6a
PLSub2	41.6bc	3.87b	42.9bc	28.3b	2.90ab	18.0a
PLSub3	43.8ab	4.02ab	47.4a	27.0b	2.91ab	18.3a

[†] Means within a column followed by different letters are significantly different ($P < 0.1$).

[‡] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 3.3. Effects of treatment on aboveground biomass nutrient (N, P, and K) concentrations, uptake, and yield collected at the R6 growth stage averaged over the two years (2014-2015).

	Biomass nutrient concentration			Biomass nutrient uptake			Biomass
Treatment[†]	N	P	K	N	P	K	yield
	-------------- g kg^{-1}---------------			-------------- kg ha^{-1}---------------			Mg ha^{-1}
UTC[‡]	8.78d	2.13a	5.23b	114.8c	27.3d	70.5c	13.5c
Fert	11.02a	1.74c	6.18a	195.9a	30.9c	109.9a	17.8a
PLBr	9.41c	2.10a	5.78a	152.6b	33.5bc	94.9b	16.4b
PLSub1	10.35b	1.98ab	6.26a	191.3a	36.1ab	116.5a	18.6a
PLSub2	9.87bc	2.03a	5.84a	182.3a	37.0a	109.4a	18.7a
PLSub3	9.66c	1.85bc	6.11a	179.6a	34.2b	113.2a	18.6a

[†] Means within a column followed by different letters are significantly different ($P < 0.1$).

[‡] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 3.4. Treatment effects on nitrogen recovery efficiency, agronomic efficiency, and grain harvest index averaged across the two years (2014 and 2015).

Treatment[†]	NRE[‡]	AE*	GHI[ϕ]
	---------- Δ kg kg^{-1}	-----------	%
UTC[¥]			53.0c
Fert	0.45a	20.1a	60.0a
PLBr	0.21b	12.2c	56.8abc
PLSub1	0.42a	17.1ab	54.5bc
PLSub2	0.37a	20.0a	57.4ab
PLSub3	0.36a	15.8bc	53.4bc

[†] Means within a column followed by different letters are significantly different ($P < 0.1$).

[‡] N recovery efficiency [NRE, (PNU_N - PNU_{UTC})/N rate, PNU = plant N uptake].

* N agronomic efficiency [AE, (GY_N - GY_{UTC}/N rate, GY = grain yield].

[ϕ] Grain harvest index (GHI, grain yield/total biomass yield).

[¥] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 3.5. Effects of treatments on grain nutrient (N, P, and K) concentrations, uptake, and grain yield averaged over the two years (2014-2015).

	Grain nutrient concentration			Grain nutrient uptake			Grain
Treatment[†]	N	P	K	N	P	K	yield
	-------------- g kg^{-1}---------------			-------------- kg ha^{-1}---------------			Mg ha^{-1}
UTC[‡]	10.80c	2.87a	2.87a	76.64d	20.46b	19.82b	7.04d
Fert	13.82a	3.37a	3.09a	148.13a	36.10a	32.62a	10.66a
PLBr	11.85b	3.19a	3.04a	109.66c	29.44a	27.73a	9.24c
PLSub1	12.02b	3.28a	3.13a	122.45b	33.27a	31.43a	10.13ab
PLSub2	12.09b	2.87a	2.87a	128.92b	30.67a	30.44a	10.65a
PLSub3	12.22b	3.19a	2.97a	121.14bc	31.74a	29.46a	9.88bc

[†] Means within a column followed by different letters are significantly different ($P < 0.1$).

[‡] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 3.6. Treatment effect on soil ammonium, nitrate, and inorganic N concentrations at post-harvest sampling date for 2014 and 2015.

	Post Harvest								
	NH_4^+-N			NO_3^--N			Inorganic N		
Treatments[†]	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
2014	mg kg^{-1}								
UTC[‡]	0.79a	0.29a	0.53a	7.27b	4.39a	4.81a	8.06b	4.68a	5.34a
Fert	0.76a	0.28a	0.35a	12.27a	5.33a	5.15a	13.03ab	5.60a	5.50a
PLBr	0.97a	0.26a	0.45a	8.00ab	2.87a	3.20a	8.97ab	3.10a	3.65a
PLSub1	1.62a	0.43a	0.50a	11.79a	6.02a	4.07a	13.41a	6.45a	4.56a
PLSub2	1.10a	0.72a	0.42a	8.18ab	7.50a	3.45a	9.28ab	8.22a	3.87a
PLSub3	1.48a	0.36a	0.32a	10.90ab	5.78a	4.39a	12.38ab	6.15a	4.71a
2015									
UTC	0.38b	0.93ab	0.96c	8.28a	3.81b	1.80b	8.66a	4.74b	2.76c
Fert	0.51ab	1.54a	0.95c	10.19a	6.41a	4.66a	10.70a	7.95a	5.61a
PLBr	0.29b	0.78ab	1.54ab	8.63a	2.97b	1.78b	8.92a	3.76b	3.32bc
PLSub1	0.72a	1.17ab	1.58a	8.98a	3.84b	2.15b	9.70a	5.00b	3.74b
PLSub2	0.72a	0.88ab	1.39b	9.05a	3.47b	2.01b	9.77a	4.34b	3.41bc
PLSub3	0.58a	0.72b	0.98bc	7.61a	3.02b	2.15b	8.19a	3.74b	3.13bc

[†] Means within each column for each year followed by different letters are significantly different at $P < 0.1$.

[‡] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry liter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

Table 3.7. Treatment effect on soil total C, total N, Mehlich-3 extractable P, and Mehlich-3 extractable K concentrations at post-harvest sampling date for 2014 and 2015.

	Post Harvest											
	Total N			Total C			M3-P			M3-K		
Treatments[†]	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
2014	----------	----------	---------- g kg^{-1}	----------	----------	----------	----------	----------	---------- mg kg^{-1}	----------	----------	----------
UTC[‡]	1.45a	0.85a	0.61c	13.66b	7.46b	4.51b	27.7d	14.6b	5.2b	155.6b	97.0a	109.5a
Fert	1.57a	0.86a	0.66abc	14.40ab	7.90ab	5.23a	51.2bcd	29.2ab	11.2a	192.5ab	89.0a	100.9a
PLBr	1.50a	0.88a	0.67ab	14.51ab	8.29a	5.13ab	38.8cd	26.8ab	9.7ab	220.8a	99.4a	103.2a
PLSub1	1.58a	0.88a	0.65abc	15.04a	8.18ab	5.14a	91.4a	26.2ab	8.3ab	212.2ab	94.7a	102.4a
PLSub2	1.57a	0.87a	0.63bc	15.05a	8.10ab	5.01ab	79.2ab	22.8ab	7.1ab	231.2a	102.2a	105.1a
PLSub3	1.57a	0.89a	0.68a	15.21a	8.34a	5.49a	75.7abc	35.1a	11.9a	195.1ab	99.4a	105.6a
2015												
UTC	1.47a	0.92ab	0.70a	14.34a	8.22a	5.19a	67.2a	33.2a	7.1a	112.0c	58.9b	42.0b
Fert	1.54a	0.86bc	0.65a	15.11a	7.84a	4.90a	81.7a	34.2a	5.8a	130.8bc	56.4b	46.8ab
PLBr	1.50a	0.84c	0.70a	14.45a	7.79a	5.18a	61.6a	35.3a	5.9a	211.3a	74.5ab	47.0ab
PLSub1	1.57a	0.92ab	0.67a	14.97a	8.40a	4.95a	80.6a	18.3a	5.8a	168.8ab	80.4a	53.0a
PLSub2	1.52a	0.88abc	0.65a	14.44a	7.95a	4.91a	61.5a	24.8a	6.5a	160.3b	87.1a	52.5a
PLSub3	1.59a	0.93a	0.69a	15.34a	8.38a	5.24a	68.9a	28.7a	7.2a	151.0bc	82.6a	49.4ab

[†] Means within each column for each year followed by different letters are significantly different at $P < 0.1$.

[‡] UTC = untreated control. Fert = urea ammonium nitrate. PLBr = poultry litter surface broadcast. PLSub1 = poultry liter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands.

3.6.2 Figures

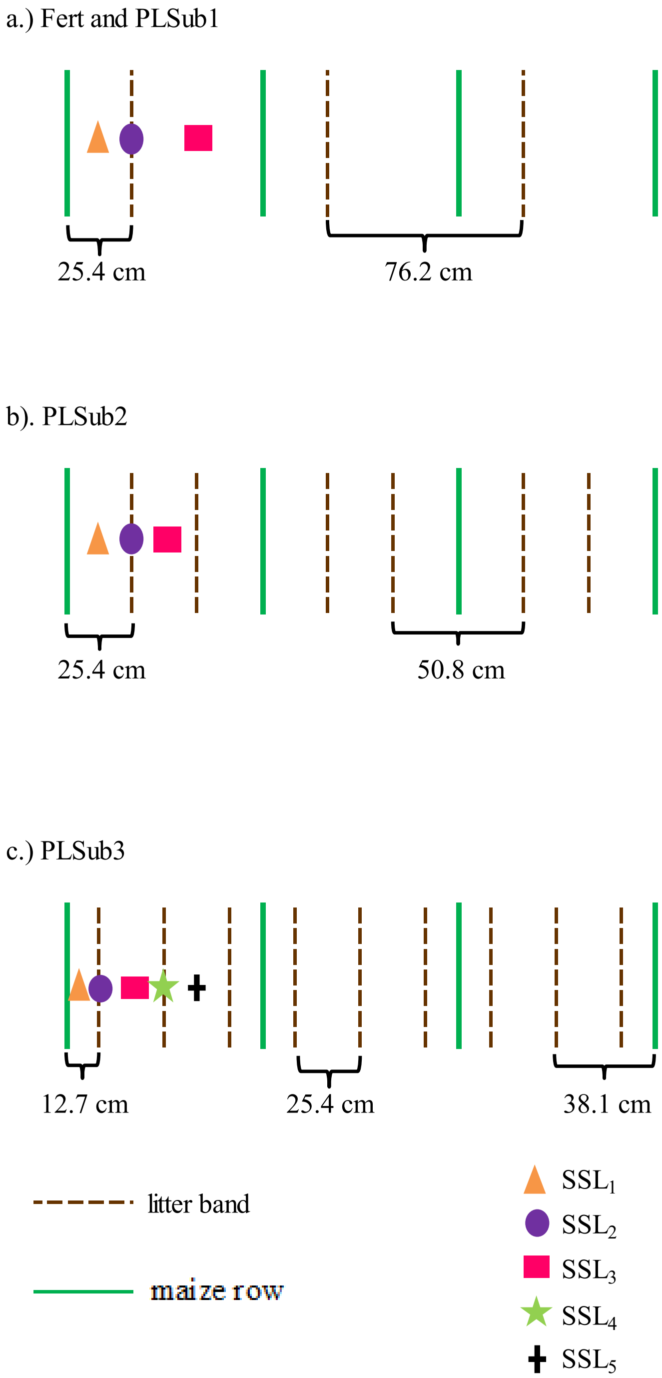

Figure 3.1. Subsurface poultry litter band placement, UAN band placement, and soil sampling schematic in relation to maize rows. Fert = urea ammonium nitrate. PLSub1 = poultry litter 1 inter-row subsurface band. PLSub2 = poultry litter 2 inter-row subsurface bands. PLSub3 = poultry litter 3 inter-row subsurface bands. SSL = soil sample location.

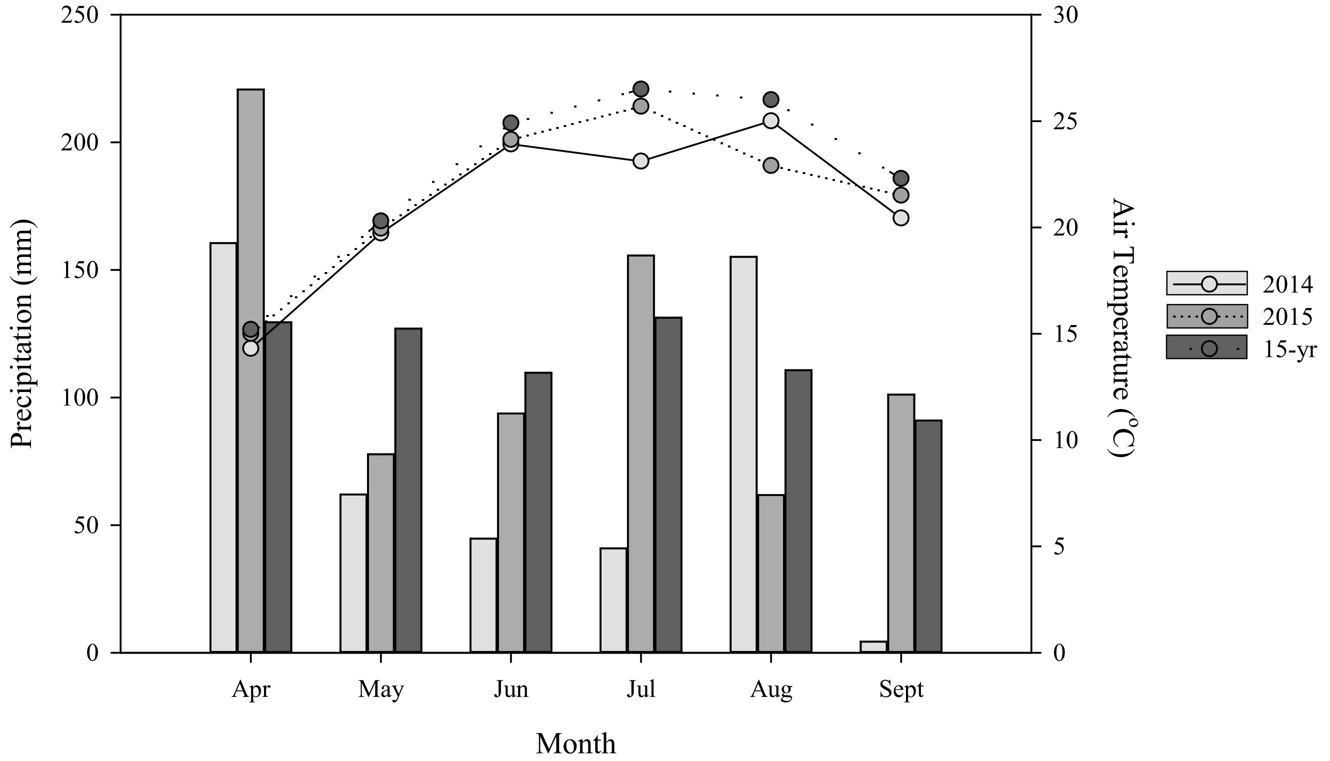

Figure 3.2. Mean monthly air temperature (lines and points) and total monthly precipitation (bars) for study site years (2014-2015) and 15-year means (2006-2020) for Warren County, KY.

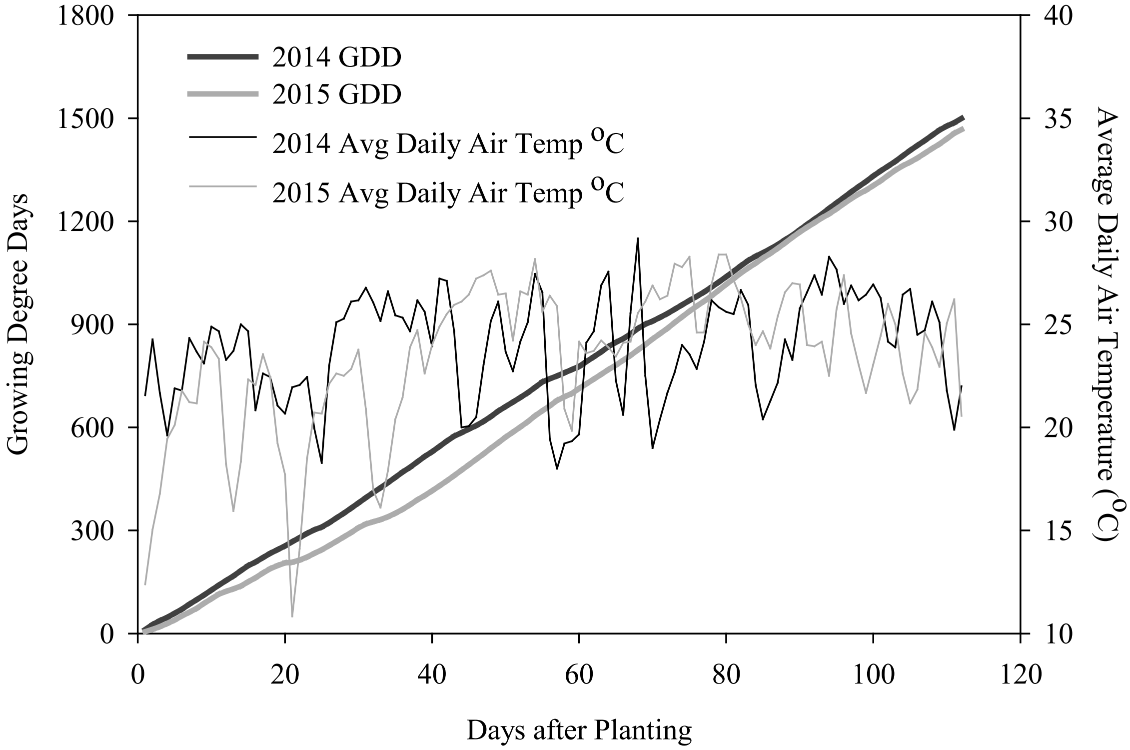

Figure 3.3. Growing degree days (GDD, thick lines) and total average daily air temperature (thin lines) following maize planting at the study site for 2014 and 2015.

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Publications

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