Nitrogen and Phosphorus Management in the Mid-Atlantic.

Catherine Stephanie Fleming

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Crop and Soil Environmental Sciences

Mark S. Reiter, Committee Chair
Joshua H. Freeman
Marcus M. Alley
Rory O. Maguire

February 22, 2013
Blacksburg, VA

Keywords: nutrient management, nitrogen, phosphorus, tomato, no-till, irrigation

Nitrogen and Phosphorus Management in the Mid-Atlantic

Catherine Stephanie Fleming

Abstract

Managing nitrogen (N) and phosphorus (P) in agricultural systems in the Mid-Atlantic is an important practice due to environmental and economic concerns. The objectives of the experiments reported in this dissertation were: (1) evaluate irrigation via evapotranspiration (ET) calculations for fresh market tomatoes grown using polyethylene mulch; (2) determine optimum N application method and rate for fresh market tomatoes; and (3) evaluate changes of soil P pools from applications of poultry litter (PL), PL amended with alum (PLA), triple super phosphate (TSP), and no P fertilizer in a long-term no-till corn-wheat-soybean rotation. A calculated irrigation rate, based on 30-year average historical weather data, of 0.5ET provided sufficient irrigation for optimum tomato yields in near average climactic seasons. Utilizing a tensiometer in a warmer and drier season than average protected against under-irrigation rates for fresh market tomatoes. Nitrogen applications ranging from 200 to 242 kg N ha^{-1} using a combination of a banded method, incorporation, and fertigation produced optimum tomato yields while significantly reducing residual post-harvest inorganic soil N compared to higher N fertilizer rates. The incorporated only method resulted in crop loss and reduced yields with N fertilizer rates greater than 224 kg N ha^{-1} in the unseasonably hot and dry season. Applications of PL and PLA to no-till land on a N basis significantly increased Mehlich-1 extractable P and 1 *M* NH_4Cl extractable P (loosely bound P) in shallow (0-5 cm) soil samples compared to 0-P control and TSP treatments. However, alum additions in PLA significantly reduced loosely bound P compared to soils fertilized with non-amended PL in shallow soil samples. Overall, results from these studies offer

insight into production practices that increase profitability and environmental stewardship in fresh market tomatoes by optimizing fertilizer and irrigation use while maintaining marketable tomato yields. Additionally, PLA reduced the amount of loosely bound P in 0-5 cm soil samples that could potentially move to surface water in these coarse textured soils.

Acknowledgements

I am fortunate to have found an amazing Hokie family at Virginia Tech that have supported me throughout my Ph.D. journey. I would like to thank my advisor, Dr. Mark Reiter for his support and guidance. Thank you for always trusting in me, despite my lack of Master's degree and farm experience. The past four years has made me realize my passion for agriculture. I would also like to thank my committee members Dr. Josh Freeman, Dr. Rory Maguire, and Dr. Mark Alley for their time, guidance, and support. Additionally, without funding from Virginia Department of Agriculture Specialty Crop Competitive Grant Program and The Maryland Grain Producers Utilization Board these projects would not have been possible.

There have been many people that have helped me along the way that I need to thank for their support and encouragement. First, Mom and Dad, thanks for letting me become who I am today. Thank you for encouraging me even after I told you I was getting a degree in dirt. To my sister, Liz, thank you for always answering the phone; even if it was to hear me vent about something you did not understand. Adam Wimer, thank you for helping me get through the toughest of the tough. You were always there for me. To my train, Katie Hoover and Sara Murrill, the last four years of my life would not have been the same without you. Dave, thank you for always splitting a pizza with me on Day 38. To all my official and unofficial officemates through the years that have kept me going with inappropriate comments, jokes, expletives while running stats, moldy coffee pots, and the occasional beers; thank you to Greg, Andrew, Jacob, Bonzey, Luther, and Emily.

Table of Contents

List of Tables

2. Optimizing Irrigation of Fresh Market Tomato Grown in the Mid-Atlantic

3. Nitrogen Rate and Application Method Management on Fresh Market Tomato Grown in the Mid-Atlantic

List of Figures

6. Appendix

List of Equations

1. Introduction

The Chesapeake Bay is the largest estuary in the United States containing over 100,000 tributaries that flow through the watershed, and into the Chesapeake Bay, supporting more than 3,200 species of plants, fish and animals (Chesapeake Bay Program, 2012). The Chesapeake Bay watershed covers over 165,000 km^2, with the shoreline stretching over 18,800 km; longer than the entire U.S. West Coast. The watershed encompasses parts of six states: Delaware, Maryland, New York, Pennsylvania, Virginia, Washington D.C., and West Virginia. The diverse Chesapeake Bay ecosystem has suffered environmentally from excessive nutrient loading that causing significant water quality concerns (Chesapeake Bay Program, 2012).

Nutrient loading speeds the natural process of algae growth, or eutrophication, in the Chesapeake Bay (Boesch et al., 2001). Nitrogen (N) and phosphorus (P) loading causes algae blooms, which can block sunlight from reaching bottom dwelling plants in the Bay that serve as food for many organisms. When sufficient nutrients for algae growth are gone, algae dies and microbial degradation causes reduced dissolved oxygen concentrations in water (Boesch et al., 2001). Reduced dissolved oxygen concentrations are detrimental to aquatic life in the Bay, which requires dissolved oxygen to survive (Officer et al., 1984). Many efforts and programs have been implemented to protect and reduce excess nutrients reaching the Bay (Boesch et al., 2001).

Soils in Virginia's coastal plain and the Mid-Atlantic are predominantly sandy loams (~650 g sand kg $soil^{-1}$) (Soil Survey Staff et al., 2013), and coarser textured soils have a greater propensity to leach nutrients like N and P compared to finer textured soils (Zotarelli et al., 2009a; Zotarelli et al., 2009b). Nutrient inflows from possible agricultural over-fertilization and over-irrigation have placed the Eastern Shore of Virginia in high nutrient load areas (Wolf, 2008a, 2008b). Modeled delivered total P to the Chesapeake Bay was greater than 0.24 kg P ha^{-1} $year^{-1}$

(Wolf, 2008b) while delivered total N was estimated to be greater than 8.0 kg N ha^{-1} $year^{-1}$ (Wolf, 2008a). Due to a negative perception of commercial agricultural operations, outcry from the general public resulted in a petition for non-point source pollution regulation of large agricultural operations on the Eastern Shore of Virginia. Large tomato (*Solanum lycopersicum*) operators utilizing polyethylene mulch and drip irrigation production systems were main targets of a December 2008 petition submitted to the State Water Control Board of the Virginia Department of Environmental Quality with the degradation of water quality from nutrient and sediment inflows being the major complaint (Terry, 2008).

The federal government is pushing for regulations to reduce nutrient loading into the Chesapeake Bay and tributaries by reducing nutrient and sediment loading in runoff (Obama, 2009). However, there is little current scientific data showing the amount of N fertilizer and irrigation that should be applied to polyethylene mulched tomatoes in the Mid-Atlantic for optimum yields as well as optimum fertilizer and irrigation use efficiency. Current commercial tomato recommendations (Kuhar et al., 2010) are outdated and do not account for current practices that include polyethylene mulch systems with precise irrigation using drip irrigation tubing, fumigation, fertigation, modern herbicide and fungicide programs, and higher yielding cultivars that might require higher amounts of fertilizer. Research has not been conducted using these practices in the Mid-Atlantic area, and published recommendations were for different production systems.

Utilizing polyethylene mulch and drip irrigation provides many benefits. Polyethylene mulch warms the soil and increases early yields, aids in irrigation water retention, inhibits weed growth, reduces fertilizer leaching, decreases soil crusting due to rainfall and soil crusting, protects fruits from organisms in the soil, and can aid in managing other pests, diseases, and viruses (Hochmuth et al., 2012). Additionally, using drip irrigation with a polyethylene mulch system ensures precise control of irrigation, fertigation, and applications of selected pesticides through the drip tube (Locascio, 2005). Research is lacking on Virginia's Eastern Shore for determining optimum rates of inputs into a controlled system of drip tubing and polyethylene much that can optimize fertilizer and irrigation use efficiencies.

Crop rotations of corn (*Zea mays*), wheat (*Triticum aestivum*), and soybeans (*Glycine max*) are popular in Virginia, and most rotations are under conservation tillage practices. The Conservation Technology Information Center (2013) reported that Virginia planted 81,147 ha of double cropped soybean in 2008, of which 76,432 ha (approximately 94%) were grown under a no-till system. About half of Virginia's cropland is fertilized with manure for N and P inputs (Mid-Atlantic Water Program, 2007). Phosphorus is a nutrient of environmental and economic concern in corn-wheat-soybean rotations fertilized with poultry litter (PL). Sims et al. (2000) stated that high values of soil P on the Delmarva (Delaware, Maryland, and Virginia) peninsula coincide with high animal densities of poultry production found in the area. Poultry litter has a low N/P ratio; thus, traditional application of PL as a fertilizer to meet N-based crop needs resulted in an over-application of P (White et al., 2010). The application of PL at a N-based rate was standard practice and built soil P to excessive levels that can lead to P runoff and leaching to surface waters (Sharpley et al., 1996; Sims et al., 2000; Maguire et al., 2008; White et al., 2010). Nutrient management regulations have been put in place in the Mid-Atlantic to reduce the potential loss of P from agricultural lands which vary from state to state (Simpson, 1998; Sharpley et al., 2003; Virginia Department of Conservation and Recreation, 2005; Wolfe et al., 2005).

Nutrient management in Virginia is managed by Virginia's Department of Conservation and Recreation (DCR). Virginia's DCR (2005) nutrient management regulations state "P applications from inorganic nutrient sources shall not exceed crop nutrient needs over the crop rotation based on a soil test." When applying manure as a fertilizer, a soil test (via Mehlich-1) is required to determine the maximum P application rate. For soils on the Eastern Shore and the Lower Coastal Plain, soil tests resulting in P concentrations below 55 mg P kg soil^{-1} can receive manure on a N basis. The degree of P saturation in a soil has shown to have a strong relationship with Mehlich-1 extractable P (M1-P) (Beck et al., 2004). Data from three physiographic regions in Virginia showed that at a 20% P saturation level, M1-P ranged from 58 to 65 mg kg^{-1}, and averaged 56 mg kg^{-1}, coinciding well with Virginia's DCR (2005) cut-off value of 55 mg kg^{-1}. Soil tests resulting in concentrations of 55-135 mg P kg soil^{-1} can receive manure on a P removal basis. Greater amounts of P via manure may be applied if the P Index Method is used (Virginia Department of Conservation and Recreation, 2005). Soil tests resulting in concentrations above 135 mg P kg soil^{-1} cannot receive fertilizer unless a P Index Method is used (Wolfe et al., 2005). Further, soils on the Eastern Shore and Lower Coastal Plain that have soil test P concentrations above 458 mg P kg soil^{-1} are above a 65% P saturation level and P fertilizer in any amount or form should not be applied (Virginia Department of Conservation and Recreation, 2005).

Phosphorus from organic materials like manure should be managed by using a method listed in the Virginia Nutrient Management Standards and Criteria (Virginia Department of Conservation and Recreation, 2005) and generally, should not be applied at rates above crop uptake unless soils are P deficient or farmers use a P Index Method. However, little data are available on the long-term behavior of P applied through PL and amended PL on no-till agronomic fields. Poultry litter is often amended with chemicals such as aluminum sulfate (alum) to reduce ammonia emissions in poultry houses (Moore and Edwards, 2005; Penn and Zhang, 2008). Poultry litter treatments like alum have also shown to reduce water soluble P in the litter (Warren et al., 2006; Moore and Edwards, 2007; Penn and Zhang, 2008), but the long-term impacts of poultry litter amended with alum (PLA) on the forms of bound P in the soil is unknown on no-till lands (Sims and Luka-McCafferty, 2002).

The studies reported in this dissertation investigate irrigation and nutrient variables and resulting environmental concerns for said practices in the Mid-Atlantic. Results will offer insight into efficient and sustainable production practices for greatest yields with the least amount of potential to lose nutrients. Maximum fertilizer use efficiency will increase profitability if optimum fertilizer and irrigation rates are used and such practices reduce potential adverse environmental impacts. These projects will provide a starting point for implementation of irrigation and fertilizer best management practices (BMPs) for Mid-Atlantic tomato growers to decrease possible agricultural nonpoint source pollution, reduce fertilizer and water waste, and protect the tributaries and the Chesapeake Bay watershed while maintaining optimum yields. It will also provide knowledge of the behavior of P in long-term, no-till lands, and how use of PL and PLA impacts the concentrations and fractions of bound P in the soil over time.

The overall objectives of these studies were to determine the optimum irrigation strategy, and optimum N fertilizer rate and application method for polyethylene mulched tomatoes grown in the Mid-Atlantic on sandy loam soils. Additional objectives included investigating effects of PL and PLA on soil pH, Mehlich-1 extractable P, and soil P fractions over time and depth in a long-term, no-till rotation in the Mid-Atlantic region.

References

Beck, M.A., L.W. Zelazny, W.L. Daniels, and G.L. Mullins. 2004. Using the Mehlich-1 extract to estimate soil phosphorus saturation for environmental risk assessment. Soil Sci. Soc. Am. J. 68:1762-1771.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. J. Environ. Qual. 30:303-320.

Chesapeake Bay Program. 2012. Bay 101 facts & figures. http://www.chesapeakebay.net/discover/bay101/facts (accessed 6 Feb. 2013).

Conservation Technology Information Center. 2013. National crop residue management survey. CTIC. http://www.ctic.purdue.edu/crm_results/ (accessed 7 Feb. 2013).

Hochmuth, G.J., R.C. Hochmuth, and S.M. Olson. 2012. Polyethylene mulching for early vegetable production in north Florida. Cir805. University of Florida, IFAS, EDIS. http://edis.ifas.ufl.edu/cv213 (accessed 22 Aug. 2012).

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2010. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Locascio, S.J. 2005. Management of irrigation for vegetables: Past, present, and future. HortTechnology 15:482-485.

Maguire, R.O., G.L. Mullins, and M. Brosius. 2008. Evaluating long-term nitrogen- versus phosphorus-based nutrient management of poultry litter. J. Environ. Qual. 37:1810-1816.

Mid-Atlantic Water Program. 2007. Virginia state-level historical trends. USDA CSREES. http://www.mawaterquality.agecon.vt.edu/VA/state_trends_menu.php (accessed 8 Feb. 2013).

Moore, P.A., and D.R. Edwards. 2005. Long-term effects of poultry litter, alum-treated litter, and ammonium nitrate on aluminum availability soils. J. Environ. Qual. 34:2104-2111.

Moore, P.A., and D.R. Edwards. 2007. Long-term effects of poultry litter, alum-treated litter, and ammonium nitrate on phosphorus availability in soils. J. Environ. Qual. 36:163-174.

Obama, B. 2009. Executive order 13508.

Officer, C.B., R.B. Biggs, J.L. Taft, L.E. Cronin, M.A. Tyler, and W.R. Boynton. 1984. Chesapeake bay anoxia - origin, development, and significance. Science 223:22-27.

Penn, C., and H. Zhang. 2008. Alum-treated poultry litter as a fertilizer source, Publ. PSS-2254, Oklahoma Cooperative Extension Service, Oklahoma State University.

Sharpley, A., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil Water Conserv. 51:160-166.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, et al. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Water Conserv. 58:137-152.

Simpson, T.W. 1998. A citizen's guide to maryland's water quality improvement act, Univ. of Maryland Coop. Ext., College Park, MD.

Sims, J.T., A.C. Edwards, O.F. Schoumans, and R.R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agricultural management practices. J. Environ. Qual. 29:60-71.

Sims, J.T., and N.J. Luka-McCafferty. 2002. On-farm evaluation of aluminum sulfate (alum) as a poultry litter amendment: Effects on litter properties. J. Environ. Qual. 31:2066-2073.

Soil Survey Staff, Natural Resources Conservation Service, and United States Department of Agriculture. 2013. Official soil series descriptions. http://soils.usda.gov/technical/classification/osd/index.html (accessed 10 Feb. 2013).

Terry, P. 2008. Prevention of degradation of water quality on the eastern shore as a result of large scale agricultural operations. State Water Control Board, Virginia Dep. Environ. Quality. http://townhall.virginia.gov/L/ViewPetition.cfm?petitionid=68 (accessed 6 Feb. 2013).

Virginia Department of Conservation and Recreation. 2005. Virginia nutrient management standards and criteria, Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation, Richmond, VA.

Warren, J.G., S.B. Phillips, G.L. Mullins, and L.W. Zelazny. 2006. Impact of alum-treated poultry litter applications on fescue production and soil phosphorus fractions. Soil Sci. Soc. Am. J. 70:1957-1966.

White, J.W., F.J. Coale, J.T. Sims, and A.L. Shober. 2010. Phosphorus runoff from waste water treatment biosolids and poultry litter applied to agricultural soils. J. Environ. Qual. 39:314-323.

Wolf, J. 2008a. Delivered yield of total nitrogen - agricultural sources. The Chesapeake Bay Program. http://www.chesapeakebay.net/maps/map/delivered_yield_of_total_nitrogen_agricultural_sources (accessed 8 Feb. 2013).

Wolf, J. 2008b. Delivered yield of total phosphorus - agricultural sources. The Chesapeake Bay Program.

http://www.chesapeakebay.net/maps/map/delivered_yield_of_total_phosphorus_agricultural_sources (accessed 8 Feb. 2013).

Wolfe, M.L., J. Pease, L. Zelazny, L. Daniels, and G. Mullins. 2005. Virginia phosphorus index version 2.0, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Zotarelli, L., M.D. Dukes, J.M. Scholberg, R. Munoz-Carpena, and J. Icerman. 2009a. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96:1247-1258.

Zotarelli, L., J.M. Scholberg, M.D. Dukes, R. Munoz-Carpena, and J. Icerman. 2009b. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96:23-34.

2. Optimizing Irrigation of Fresh Market Tomato Grown in the Mid-Atlantic.

2.1. Abstract

Determining irrigation requirements for current fresh market tomato production is essential to obtain optimum yields, uphold cost-effective water use efficiency, and reduce the propensity for nitrate leaching. The objective of this study was to determine the appropriate irrigation rate to reduce N loss for polyethylene mulched fresh market tomatoes grown in Virginia. This study investigated irrigation regimes by applying water based on evapotranspiration (ET) calculations. Tomatoes were grown using 0.0ET, 0.5ET, 1.0ET, 1.5ET, and 2.0ET. Additional irrigation treatments involved tensiometers programmed to irrigate at soil moisture set points of -20, -40, and -60 kPa. Measurements included fruit yield, total N uptake, total soil N, and inorganic NO_3-N at 0.00-0.25, 0.25-0.50, and 0.50-0.75 m depths. Overall, the 0.5ET treatment provided optimum yields in all growing seasons except Spring 2010, which was unseasonably warm and dry. Applying 0.5ET in conjunction with tensiometer readings supplied sufficient irrigation water and provided a measurement of soil moisture to monitor and make adjustments in unseasonable growing seasons. Residual soil NO_3-N generally mirrored yield at 0.00-0.25 m; greater yields resulted in less residual soil NO_3-N. In most treatments throughout the course of this study, plant N uptake + fruit N uptake accounted for most of the N fertilizer applied (68-151%). In conclusion, an irrigation rate of 0.5ET accompanied by a tensiometer provided minimal irrigation inputs to obtain optimum marketable yields while also reducing NO_3-N in topsoil that might be prone to leaching.

2.2. Introduction

Tomatoes (*Solanum lycopersicum*) are an extensively grown vegetable crop on the Eastern Shore of Virginia (*Accomack* and *Northampton Counties)*. In 2011, 1,862 hectares (ha) of commercial fresh market tomatoes were harvested in Virginia, with an estimated value of 47.5 million dollars (USDA-National Agricultural Statistics Service, 2011). Commercial producers in the United States harvested a total of 40,352 ha of fresh market tomatoes with Virginia ranked third in harvested acreage after California and Florida (14,164 ha and 12,545 ha, respectively) (USDA-National Agricultural Statistics Service, 2011). In regards to value of production, Virginia ranked fourth behind Florida, California, and North Carolina (565, 378, and 53 million dollars, respectively) (USDA-National Agricultural Statistics Service, 2011). With so many ha dedicated to tomatoes grown in close proximity to the Chesapeake Bay and tributaries, nitrate leaching and runoff are of high concern.

Drip irrigation combined with polyethylene mulch is a common practice for commercially grown fresh market tomatoes in the Mid-Atlantic. Drip irrigation and polyethylene mulch systems reduce evaporation and therefore increase water use efficiency on coarse soils with low water holding capacities, among many other benefits (Zotarelli et al., 2009a; Hochmuth et al., 2012). Coarse sandy soils have water holding capacities of 8% to 15%, while fine textured soils may have water holding capacities over 40% (Locascio, 2005). With a lower water holding capacity in coarse soils, proper irrigation is necessary to obtain optimum yield, uphold cost-effective water use, and reduce the propensity for dissolved nutrients to leach (Zotarelli et al., 2009b).

Determining suitable timing and quantity to irrigate is essential for efficient crop production. Stanley and Clark (2004) suggested irrigating with frequent short durations using drip irrigation on soils with low water holding capacities to reduce water loss. A crop’s water requirement is determined by the evapotranspiration (ET) that takes place from the system. In-situ measurements of actual soil moisture can also be used. Smajstrla et al. (1997) discussed irrigation scheduling on sandy soils in Florida, and suggested using a tensiometer that provided a direct measurement of soil matric potential at the installed depth. In addition to calculated ET that determined the amount to irrigate, a tensiometer can indicate when to irrigate.

A study performed by Locascio and Smajstrla (1996) examined calculated irrigation rates and tensiometer based treatments and applied multiple rates of irrigation based on calculated pan evaporation to polyethylene mulched tomatoes on a fine sandy soil near Gainesville, FL. They observed in dry years, quantities between 0.5- and 1.0-pan-evapotranspiration produced maximum yields. Maximum production was obtained by using a tensiometer scheduled to initiate irrigation at -10 kPa, with a water output of 0.35×pan-evapotranspiration. Soil samples (0-15 cm) taken throughout the growing seasons showed that in treatments receiving irrigation, water quantity did not influence water extractable N (NO_3-N + NH_4-N). However, a 0-water treatment did result in higher water extractable N than all irrigated treatments, likely due to lesser yields in two out of three growing seasons. The tensiometer treatment extractable soil N values were similar to the average of all irrigated treatments. Marketable yield in the tensiometer treatment was not significantly different from 0.75-pan-evapotranspiration yield in all three growing seasons.

Evapotranspiration is a measurement of water loss from the cropping system that occurs through two processes: (1) evaporation from the soil surface; and (2) transpiration from plant leaves. Evapotranspiration is commonly reported in millimeters per day and directly relates to the plant’s water need. Irrigation requirements are equal to the amount of water lost through ET minus water deposited through precipitation (Doorenbos and Pruitt, 1977; Allen et al., 1998).

Growth stage of a plant impacts the water requirement for a plant. Doorenbos and Pruitt (1977) reported that tomatoes’ initial, crop development, mid-season, late season, and total growing period from planting (seeding) to harvest are approximately 30, 40, 45, 30, and 145 days, respectively for Mediterranean climates. However, Doorenbos and Pruitt (1977) also indicated that these growing periods may vary from region to region, and with different crop varieties. Growth stages can also be determined by physiological maturity and groundcover of the crop. The initial stage occurs from seed germination to approximately 10% groundcover. Crop development occurs after the end of the initial stage until approximately 80% groundcover. Mid-season stage follows and lasts until the plants begin to mature. Maturity is indicated by discoloring of leaves in beans (*Phaseolus vulgaris*), leaves falling off in cotton (*Gossypium* spp.), and will extend until harvest for most plants. Lastly, late-season stage continues until full maturity (Doorenbos and Pruitt, 1977).

A crop coefficient (K_c), a number used in calculating ET, changes with the growth stage of a plant. These values are associated with increasing canopy growth and associated increased transpiration. Allen et al. (1998) reported K_c values for non stressed, well managed crops in subhumid climates with relative humidity above 45% and wind speeds above 2 m sec^{-1} for three growth stages: initial stage, mid-season stage, and end of the late season stage ($K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$, respectively). For vegetables in the Solanum family (*Solanaceae*), $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ were reported as 0.6, 1.15 and 0.80, respectively (Allen et al., 1998). Specifically for tomatoes, Allen, et al., (1998) reported no value for $K_{c\ ini}$, however $K_{c\ mid}$ and $K_{c\ end}$ values were 1.15 and 0.70-0.90, respectively. Doorenbos and Pruitt (1977), reported no value for $K_{c\ ini}$, while $K_{c\ mid}$ and $K_{c\ end}$ values were 1.05 and 0.60, respectively, for tomatoes grown under relative humidity greater than 70% and winds of 0-5 m sec^{-1}.

The use of drip irrigation and polyethylene mulch decreases evaporation from the field system and therefore decreases K_c (Allen et al., 1998; Amayreh and Al-Abed, 2005). Haddadin and Ghawi (1983) studied the effect of polyethylene mulch on field grown tomato on sandy loam soil in the Jordan Valley of Israel and found that the use of black plastic mulch significantly increased yield and water use efficiency. The FAO reported that Haddadin and Ghawi's (1983) research found a reduction of K_c by 35% for tomatoes when using polyethylene mulch with drip irrigation (Allen et al., 1998). Amayreh and Al-Abed (2005) found similar results with a 36% reduction in K_c over the entire growing season for polyethylene mulched, drip irrigated tomatoes grown on a silty clay soil in the Jordan Valley. More specifically, Amayreh and Al-Abed (2005) found a 35% reduction of K_c in the development stage (initial and crop development stages), a 31% reduction of K_c in mid-season, and a 40% reduction of K_c in the end-season stage.

Excessive irrigation on coarse soils with low water holding capacities can lead to nutrients leaching from the soil. Leached nutrients can be measured using suction cup lysimeters installed below the cop root zone, and have been used successfully for many years (Rhodes and Oster, 1986; Grossmann and Udluft, 1991; Ahmed et al., 2001; Zotarelli et al., 2007). A vacuum is applied on the lysimeter, creating suction through the porous ceramic cup installed at the desired subsurface depth. The suction pulls available soil water in through the pores of the ceramic cup, and stores the water for collection. Zotarelli et al. (2007) monitored nitrate leaching on sandy soil near Citra, Florida over time under drip irrigated tomatoes by using suction cup lysimeters. A factorial arrangement of two irrigation rates (a low volume = quantified irrigation controller system treatment, and a high volume = time-fixed irrigation schedule treatment) and two N fertilization rates (208 and 312 kg N ha^{-1}, respectively) were observed. Nitrogen loading rates were estimated by multiplying net drainage volumes from adjacent drainage lysimeters by nitrate concentrations collected from the suction cup lysimeters. Nitrate-N leachate values were similar for both irrigation rates under the 208 kg N ha^{-1} fertilization rate. However, under the 312 kg N ha^{-1} fertilization rate, differences in nitrate-N leachate were observed between the low and high volume irrigation rates (2.7 vs. 33.8 kg N ha^{-1}, respectively) (Zotarelli et al., 2007). Ahmed et al. (2001) also proved successful in determining nitrate concentrations using suction cup lysimeters on a sandy soil in the coastal plain of Western Australia. A field study was implemented to compare soil water sampled from ceramic suction cup lysimeters that during installation were back-filled with either sand or a silica slurry. Results showed that although mean NO_3-N concentrations were very similar, there was a greater standard deviation using sand as a back-fill (Ahmed et al., 2001).

If nutrients leach below the effective root zone, it will not be absorbed by the plant and is lost from the production system, reducing fertilizer use efficiency. Machado and Oliveira (2005) reported that rooting depth of tomatoes in sandy soil was independent of three different water regimes and three different drip irrigation depths. Zotarelli et al. (2009b), observed tomato root systems under several irrigation treatments on sandy soil near Citra, Florida. Root distribution patterns showed that independent of irrigation treatment, root length density concentrated around drip tape emitters. Zotarelli et al., (2009b), Oliveira et al., (1996) and Machado and Oliveira (2005) agree that the majority of tomato roots are concentrated in the upper 40 cm of the soil profile. Therefore, suction cup lysimeters installed below 40 cm collect water that has exited the effective root system of tomatoes, and consequently, the production system.

The objective of this study was to determine an optimal irrigation regime for polyethylene mulched fresh market tomatoes grown on a sandy loam soil in the Mid-Atlantic. Ideally, the regime limits the amount of fertilizer leached below the root zone and conserves irrigation water usage, while providing optimum marketable yields.

2.3. Materials and Methods

This study was established in the spring and fall seasons of 2009, 2010, and 2011 (6 site years) on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludults) (Soil Survey Staff, 2013) at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, Virginia (37.59°N 75.77°W). Bojac sandy loam has approximately 590 g sand kg soil^{-1}, 300 g silt kg soil^{-1}, and 110 g clay kg soil^{-1} in the Ap horizon (0-46 cm) and approximately 430 g sand kg soil^{-1}, 420 g silt kg soil^{-1}, and 150 g clay kg soil^{-1} in the Bt horizon (46-56 cm). The soil was conventionally tilled, and 0.2 m raised beds were constructed on 1.8 m centers. In a single pass, beds were fumigated with methyl bromide and chloropicrin (67:33, w:w) at the rate of 336 kg ha^{-1}, and 0.5 mm thick polyethylene mulch was applied over the bed. Under the mulch, we applied Aqua-Traxx drip tubing (Toro, Riverside, CA 92504) with emitters spaced 30 cm apart and a delivery rate of 5.6 L 100 m^{-1} min^{-1} at 0.55 bar was placed 8 to 10 cm from the bed center. Four to five week old tomato seedlings ('BHN602') were transplanted on 46 cm in-row spacings, resulting in a plant population density of approximately 12,000 plants ha^{-1}. Tomato seedlings were transplanted in 12 m single row plots on May 20, 2009, May 21, 2010, and May 25, 2011, for the spring season and on July 17, 2009, July 13, 2010, and July, 28, 2011, for the fall season. All other production practices were conducted according to Wilson et al. (2012).

2.3.1. Calculating Evapotranspiration

Evapotranspiration for a specific crop (ET_c) was calculated by multiplying a reference ET (ET_o) by the appropriate crop coefficient (K_c) (Eq. 2.1).

Eq. 2.1 Crop Evapotranspiration

Where:

ET_c = crop ET

ET_o = reference ET

K_c = crop coefficient

Reference ET (ET_o) was based on a hypothetical grass surface that is only affected by climactic conditions; soil conditions are not considered. The FAO suggested the use of the Hargreaves equation (Eq. 2.2) to calculate the hypothetical grass surface ET_o (Allen et al., 1998).

Eq. 2.2: Hargreaves Equation to determine Reference Evapotranspiration

Where:

ET_o = reference ET

T_{mean} = mean temperature (ºC)

T_{max} = maximum temperature (ºC)

T_{min} = minimum temperature (ºC)

R_a = extraterrestrial solar radiation (mm day^{-1}) (found in Table 2.6 in Allen et al., 1998).

A crop coefficient (K_c) is a unitless ratio of ET_c/ET_o that can be found in several FAO publications (Doorenbos and Pruitt, 1977; Allen et al., 1998) for vegetables, forages, fruit trees, and other crops. The value varies based on crop, growth stage, and management practices (Smajstrla et al., 1997). Most crop coefficients range from 0.5 to 1.2 with higher values during mid-season growth as water requirements are increased, and lower values during initial and late-season growth as water requirements decrease.

Fresh market tomato evapotranspiration (ET_c) was calculated by multiplying K_c by a reference ET (ET_o) (Eq. 2.1). Described by Allen et al. (1998), ET_o was determined using the Hargreaves equation via temperature and extraterrestrial solar radiation (Appendix, Table 6.1). A 1971-2000 Monthly Climate Summary from the Southeast Regional Climate Center (2007) for Painter, VA (37.35°N 75.49°W) provided monthly minimum and maximum temperature values. Extraterrestrial solar radiation for Painter, VA was found from Table 2.6 of Allen et al., (1998) by using an estimated latitude of 38°N.

To calculate ET_c for different growth stages, K_c was interpolated from Doorenbos and Pruitt (1977) and Allen et al. (1998). The K_c for tomatoes was estimated at 0.60 for $K_{c\ ini}$ (Allen et al., 1998), and $K_{c\ mid}$ and $K_{c\ end}$ values of 1.05 and 0.60 (Doorenbos and Pruitt, 1977), respectively. The K_c value during the crop development stage was estimated to be 0.83, an average of the values used for $K_{c\ ini}$ and $K_{c\ mid}$.

Doorenbos and Pruitt (1977) provided the number of calendar days in each crop growth stage; however, Allen et al. (1998), suggested only using the listed days as a general guide and for comparison purposes only. Categorizing crop growth stages by plant development stages gives the ability to account for plant variety, climate, and cultural practices. Therefore, crop growth stage was based on physiogical maturity of the plant to account for varying growth advancements per year.

Crop coefficient values were reduced accordingly in calculating ET_c over the growing season due to the use of polyethylene mulch. Crop coefficients during initial growth stage, crop development stage, and mid-season stage were reduced by 35%, 35%, and 31%, respectively (Amayreh and Al-Abed, 2005). Table 6.2, Table 6.3, and Table 6.4 (Appendix) show ET_c

calculations for initial, crop development, and mid-season stages, respectively, using reduced K_c values.

2.3.2. Calculating Irrigation

Irrigation needed for a crop is the amount of evapotranspiration from the system (ET_c) minus precipitation (Doorenbos and Pruitt, 1977; Allen et al., 1998). Long-term average precipitation data were used from the Southeast Regional Climate Center (2007). A 1971-2000 Monthly Climate Summary for Painter, VA was used for average monthly total precipitation estimates. Historical rainfall data were used to calculate average daily precipitation and subtracted from ET_c to determine daily irrigation for respective month and growth stages of the crop. Irrigation calculated by subtracting precipitation from ET_c, as defined by Doorenbos and Pruitt (1977) and Allen et al. (1998), was labeled as treatment “1.0ET” in this study.

2.3.3. Irrigation Treatments

Five irrigation treatments were set using automatic timers (Hunter Smart Valve Controller, San Marcos, CA, 92069). The total calculated daily watering time per treatment was halved to irrigate twice a day, and applied 7 days a week, to deliver 0.0ET, 0.5ET, 1.0ET, 1.5ET, and 2.0ET. In spring and fall seasons of 2009, one tensiometer treatment was also implemented. In spring and fall seasons in 2010 and 2011, three tensiometer treatments were implemented. Irrigation for the tensiometer treatments was triggered automatically with a wired tensiometer (Model RA, Irrometer, Riverside, CA, 92561) installed in the active root zone (30 cm depth). Irrigation for the tensiometer treatments initiated after the tensiometer’s reading raised above preset values of -20, -40, or -60 kilopascal (kPa), respectively, based on the treatment (only a -40 kPa value was used in 2009). An automatic timer wired into the tensiometer/irrigation system switched irrigation on for a maximum possibility of nine times per day. Each of the nine possible irrigation periods were set for the duration of time calculated for daily 0.5ET. This gave the possibility of the automatic tensiometer system to water between 0.0×ET and 4.5×ET.

2.3.4. Fertilizer Application

A total of 224 kg N ha^{-1} was applied over the growing season. A pre-plant rate of 96 kg N ha^{-1} using ammonium nitrate (340 g N kg $fertilizer^{-1}$) was incorporated into the plant beds using a rotary tiller prior to laying polyethylene mulch. The remaining N was applied using liquid urea-ammonium nitrate (320 g N kg $fertilizer^{-1}$) through bi-weekly fertigation throughout the growing season during pre-scheduled irrigation events. Nitrogen rates used in fertigation increased as the growing season progressed to match plant N uptake (Wilson et al., 2012). Fertigated N was applied at 0.22, 0.32, 0.45, 0.68, 1.00, and 1.10 kg N day^{-1} for time periods 0-14, 15-28, 29-42, 43-56, 57-77, and 78-98 days after transplanting, respectively. All treatments received the same amount of N fertilizer prior to planting and throughout bi-weekly fertigation.

2.3.5. Lysimeters

A suction cup lysimeter was installed in the center of each plot between two plants to collect soil leachate. Lysimeters consisted of 3.81 cm, schedule 160 PVC pipe (4.82 cm outer diameter) with a 5 cm in length porous ceramic cup (Item No. 0653X01-B01M3, Soilmoisture Equipment Corp., Santa Barbara, CA) affixed to the bottom of the PVC pipe with epoxy. A removable stopper fitting for the top consisted of a polyethylene tube that extended from the bottom interior of the lysimeter cup, up through a size 10 black rubber stopper seated in the PVC pipe. A flexible rubber tube was fitted over the polyethylene tube above the stopper and secured by a stainless steel worm gear hose clamp. Lysimeters were installed with the bottom of the ceramic cup at a 50 cm depth, below the effective tomato root zone (Oliveira et al., 1996; Machado and Oliveira, 2005). Installation was completed by augering to the appropriate depth and back-filling around the lysimeter with silica flour slurry (200 mesh, Soilmoisture Equipment Corp., Santa Barbara, CA) (Ahmed et al., 2001).

Once per week, a 40 kPa vacuum was placed on the lysimeter. After the vacuum was created in the lysimeter, the rubber tube was folded over twice and secured to ensure a constant vacuum. After 30 min, lysimeter leachate was collected by releasing the internal vacuum, and placing suction on the rubber tube until all leachate was removed into a secondary collection bottle. Samples were acidified to $pH<2.0$ and refrigerated at 4° C until analysis. Leachate samples were analyzed for ammonium-N (Mulvaney, 1996) and nitrate-N+nitrite-N (Mulvaney, 1996) colormetrically using Lachat QuickChem 8500 (Hach Company, Loveland, CO 80538).

2.3.6. Nitrogen Status Measurements

Petiole sap nitrate-N tests and Normal Difference Vegetation Index (NDVI) readings were performed when fruit was approximately 5 cm in diameter. Petioles were collected from 6 plants per plot from the upper most fully expanded leaf (Hochmuth, 1994; Ozores-Hampton et al., 2012). The sap of all six petioles was combined and nitrate concentrations (NO_3-N) were found using a Cardy meter (Spectrum Technologies, Plainfield, Illinois 60585). A handheld GreenSeeker® (Model 505, NTech Industries, Ukiah, CA 95482) was used to determine NDVI readings. The GreenSeeker® collected data from the entire length of the plot at 30 cm distance from the sides of the plants. Readings taken on the top of the row would have confounding results from string, stakes, etc. NDVI readings from GreenSeeker® depict in-season N status of plants and correlate to plant biomass and plant N concentration (Osborne, 2007).

2.3.7. Yield

Yield was calculated by harvesting mature green fruit two to three times, depending on the season, which is the standard agronomic practice. Fruit was separated by size according to

USDA standards (USDA - Agricultural Marketing Service, 1991), weighed, and counted. A small size designation has a minimum diameter of 5.40 cm and a maximum diameter of 5.79 cm. A medium size designation has a minimum diameter of 5.72 cm and a maximum diameter of 6.43 cm. A large size designation has a minimum diameter of 6.35 cm and a maximum diameter of 7.06 cm. An extra-large size designation is any fruit with a minimum diameter of 6.99 cm or greater. Culls (unmarketable, blemished fruit) were included with the small fruit size and labeled as unmarketable. Medium, Large, and Extra-Large fruit weights were combined to determine marketable yield.

2.3.8. Post-Harvest Sampling

After plants were harvested, plant, fruit, and soil samples were collected. One plant per plot was collected, dried, and weighed to estimate total above-ground biomass. Plant samples were ground and analyzed for total N via combustion (Bremner, 1996) (vario EL cube, Elementar, Elementar Americas, Inc., Mt. Laurel, NJ 08054) to determine plant N concentrations. Nitrogen concentration in the plant material was subsequently multiplied by plant biomass to determine total above-ground N uptake in the plant.

Five fruit from each plot were collected, dried, ground, and analyzed for total N via combustion (vario EL cube, Elementar, Elementar Americas, Inc., Mt. Laurel, NJ 08054) to determine fruit N concentration. Nitrogen concentration in the fruit material was multiplied by fruit biomass to determine total above-ground N uptake in the fruit. Fruit was assumed to contain 94% water (Angelini and Magnifico, 2010). Therefore, total yield was multiplied by 6% to determine fruit biomass. Plant and fruit N concentrations multiplied by total above-ground biomass and total fruit yield, respectively, determined total system (plant + fruit) N uptake.

Soil samples from 0.00-0.25 m, 0.25-0.50 m, and 0.50-0.75 m depths were collected. For each depth, two cores were taken on the side of the bed opposite of the drip tape, and four cores on the side of the bed with the drip tape; two between the drip tape and the edge of the bed and two between the drip tape and the center of the bed. Soil samples were air dried and ground. Soil analysis consisted of total N via combustion (Bremner, 1996) (vario EL cube, Elementar, Elementar Americas, Inc., Mt. Laurel, NJ 08054), and KCl soil extracts. Soil was extracted with 2 *M* KCl at a 1:10 soil:2 *M* KCl ratio, shaken for 1 h, and filtered (Mulvaney, 1996). Extracts were analyzed within 24 hours for nitrate-N+nitrite-N colormetrically using a Lachat QuickChem 8500 continuous flow analyzer (Hach Company, Loveland, CO 80538).

2.3.9. Statistics

The overall experimental design was a randomized complete block design that had treatments replicated four times, giving a total plot combination of 20 plots in Spring 2009, 24 plots in Fall 2009, and 32 plots in both spring and fall seasons of 2010 and 2011. Statistical analysis was conducted in JMP (JMP, Version 9. SAS Institute Inc., Cary, NC, 2010). An analysis of variance was performed and if significance was present (P<0.10), separation of means was conducted using Student's t least significant difference values established at *alpha* = 0.10. Year was significant for all data sets; therefore, all data were analyzed individually by year.

In Spring 2009, treatments 2.0ET and the tensiometer treatment (Tens40) encountered excessive pressure in the drip tubing, and were inflicted with large leaks in the plots. Therefore, these treatments were removed from statistical analysis due to the confounding circumstances.

2.4. Results and Discussion

2.4.1. Yield

In Spring 2009, 0.5ET and 1.0ET yielded significantly more marketable fruit than 1.5ET (70931, 67943, and 49451 kg marketable fruit ha^{-1}, respectively) (Table 2.1). In Fall 2009, Tens40 yielded similar to 0.5ET (50048 and 44295 kg marketable fruit ha^{-1}, respectively) and greater than other treatments. However, out of the calculated irrigation treatments, 0.5ET was similar to 1.0ET and 1.5ET and higher yielding than 0.0ET and 2.0ET.

In Spring 2010, 1.5ET, 2.0ET, and Tens40 produced the greatest yields with 53971, 46328, and 47595 kg marketable fruit ha^{-1}, respectively (Table 2.1). 0.0ET resulted in significant yield loss, producing significantly less marketable yield than every other treatment. The Spring 2010 season was warmer and had less cumulative precipitation in May, June, and July than 2009, 2011, and the 30-year averages. Due to the unseasonably warm dry season, it was expected that higher calculated ET treatments would result in greater yields. In Spring 2010, the higher calculated irrigation treatments (1.5ET and 2.0ET) were not significantly different from the Tens40 treatment, showing that the use of a tensiometer set at -40 kPa might protect yields in warmer and dryer growing seasons. In a sandy loam, soil is at field capacity at -10 to -20 kPa, and at -40 to -60 kPa, 50% of available water is depleted (Wilson et al., 2012). In Fall 2010, there were no significant differences between treatments and average yield was 32836 kg marketable fruit ha^{-1}.

In Spring 2011, 0.0ET produced significantly less marketable fruit than every other treatment. There were no other significant differences in Spring 2011 between other irrigation treatments. In Fall 2011, there were no significant differences between treatments and yields averaged 29737 kg marketable fruit ha^{-1}.

Overall, marketable yields for most treatments were greater than average Virginia fresh market tomato production for 2009, 2010, and 2011 (33612, 23537, and 24640 kg fruit ha^{-1}

respectively) (USDA-National Agricultural Statistics Service, 2011). However, weather factors including temperature and rainfall influenced yields in several calculated irrigation treatments, as seen in Spring 2010. In an unseasonably hot and dry growing season, calculating evapotranspiration via historical averages will not supply sufficient irrigation for optimum yields. Locascio and Smajstrla (1996) saw in very dry seasons, a 0-irrigation treatment (0.0ET) resulted in poor plant growth and water application to subsequent treatments significantly increased fruit yield. This is similar to our results in Spring 2010, which was very dry. Although yield in 0.5ET was significantly less than higher calculated ET irrigation rates (1.5ET was highest yielding in Spring 2010), a significant increase in yield was observed between 0.0ET and 0.5ET. Additionally, 0.5ET in Spring 2010 produced yields near the average yield for Virginia in 2010 (22523 and 23537 kg fruit ha^{-1}, respectively).

In Spring seasons, treatment 1.0ET applied approximately 5.8 mm water per day at season peak. Peak water application in Fall seasons was 3.3 mm per day. Less irrigation was needed in fall seasons due to milder temperatures and higher average rainfall. The lack of significant differences between treatments in Fall 2010 and Fall 2011 coincides with findings in Locascio and Smajstrla (1996) where marketable yield was not affected by water application in a season with greater rainfall (averaging 3.4 cm $week^{-1}$) than other seasons, similar to Fall conditions in Virginia.

Incorporating daily weather readings into ET calculations would be beneficial in unseasonable growing conditions; however, producers would be reluctant to continuously vary their irrigation regimes and change the timers that control irrigation. An alternative to daily ET calculations is to use a tensiometer to monitor soil moisture. The calculated 0.5ET treatment provided optimum yields in all growing seasons (except Spring 2010), and were even numerically higher in seasons where there were no significant differences in calculated irrigation treatments (Fall 2010, and Fall 2011). Applying 0.5ET rate of irrigation accompanied by the use of a tensiometer in the field will supply sufficient irrigation and provide an in-situ measurement of soil water tension to monitor and make adjustments in unseasonable growing seasons. This recommendation is similar to findings by Locascio and Smajstrla (1996) where highest marketable tomato yields were obtained with 0.75ET and was similar to yields obtained using a tensiometer to schedule irrigation.

2.4.2. Petiole Sap Nitrate-N

In Spring 2009, 1.0ET had significantly higher petiole sap NO_3-N than 0.5ET (792 and 501 mg NO_3-N kg^{-1}, respectively; *P* value = 0.0738; $LSD_{0.10}$ = 196); while 1.5ET (648 mg NO_3-N kg^{-1}) was not significantly different from either 1.0ET or 0.5ET. Although 0.5ET was significantly lower than 1.0ET, it still falls in the sufficiency range of 400-600 mg N kg^{-1} (Hochmuth, 1994). In all subsequent seasons, there were no significant differences in petiole sap NO_3-N concentrations between treatments. Generally, irrigation did not influence petiole sap NO_3-N, as sufficient N concentrations were present. Additionally, season averages consistently fell above the suggested sufficiency concentration range of 400-600 mg N kg^{-1} nitrate-N (Hochmuth, 1994).

2.4.3. NDVI

In Spring 2009, 0.5ET and 1.0ET had significantly higher NDVI averages than 1.5ET (0.93, 0.91, and 0.86, respectively; *P* value = 0.0261; $LSD_{0.10}$ = 0.04). A lower NDVI average might have been caused by a greater early season fruit-set; immature tomatoes have a lighter green color than plant leaves. In all subsequent seasons, however, there were no significant differences in NDVI averages between treatments. Generally, irrigation did not influence NDVI averages.

Difficulties in obtaining consistent NDVI data for fresh market tomatoes were likely due to production practices. Fresh market tomato plants are staked and strung to keep plants vertical. By doing so, both the darker green upper side and lighter green underside of the leaves are often exposed. Additionally, readings were performed when small immature green fruit were present. The multiple shades of green from the upper side and underside of leaves, and fruit present likely confounded results. Ulissi et al. (2011) found a chlorophyll meter reading (SPAD) to be a useful tool in low input processing tomato production models; however, no literature is available using a Greenseeker® on fresh market tomatoes.

2.4.4. Plant Nitrogen Concentration

Nitrogen concentration in plant material (Appendix, Table 6.5) differed significantly in one growing season: Spring 2010. Treatments 0.0ET and 0.5ET had significantly more g N kg plant material^{-1} than all other treatments (33.71 and 30.81 g N kg plant material^{-1}, respectively). Treatments 2.0ET and Tens40 had significantly less g N kg plant material^{-1} than all other treatments. No significant differences were observed in subsequent growing seasons. Averages for Spring 2009, Fall 2009, Fall 2010, Spring 2011, and Fall 2011 were 23.67, 35.29, 37.00, 26.25, and 38.59 g N kg plant material^{-1}, respectively. According to standard values for tissue analysis for Florida (Hochmuth et al., 2004), our plant tissue analysis tested mainly in adequate (20 to 30 g N kg^{-1}) and high (>30 g N kg^{-1}) status levels for harvest period sampling. The lack of significant differences between treatments and adequate and high plant tissue status levels show that irrigation (neither shortages nor excess) impacted N concentration in plant material.

Plant N uptake (leaves and stems) showed no significant differences in any growing season (Appendix, Table 6.6). Irrigation did not influence total N uptake in the plant. Averages for Spring 2009, Fall 2009, Spring 2010, Fall 2010, Spring 2011, and Fall 2011 were 53.03, 134.12, 82.46, 83.75, 69.64, and 111.49 kg N ha^{-1}, respectively. Zotarelli et al. (2009a) observed plant N uptake (leaves and stems) accumulations of 33.9, 43.6, and 53.5 kg N ha^{-1} in spring tomato studies conducted in Florida fertilized with 176 kg N ha^{-1}. Our fall season plant N uptake values are larger than those found by Zotarelli et al. (2009a) and may be due to larger vegetative growth and less fruit set in these seasons.

2.4.5. Fruit Nitrogen Concentration

Nitrogen concentration in fruit (Appendix, Table 6.7) was significantly different between treatments in one growing season: Fall 2010. Treatment Tens40 had the highest fruit N concentration and was similar to treatments 1.5ET, Tens20, and Tens60. No significant differences were observed in subsequent growing seasons. Averages for Spring 2009, Fall 2009, Spring 2010, Spring 2011, and Fall 2011 were 42.07, 51.88, 46.72, 46.07, and 52.33 g N kg dry fruit $material^{-1}$, respectively.

As expected, significant differences in fruit N uptake (Table 2.2) mirrored growing seasons with significant differences in marketable yield (Table 2.1). In Spring 2009, 0.5ET and 1.0ET had significantly higher fruit N uptake than 1.5ET. In Fall 2009, 0.5ET and Tens40 had significantly more fruit N uptake than other treatments. In Spring 2010, 1.5ET, 2.0ET, and Tens40 had significantly more fruit N uptake than all other treatments while 0.0ET was significantly lower than all other treatments. In Spring 2011, 0.0ET was significantly lower than all other treatments. There were no significant differences found in Fall 2010 and Fall 2011. Fruit N uptake for all seasons ranged from 53.20 to 231.10 kg N ha^{-1}. This uptake range showed that 24% to 103% of the fertilizer applied (224 kg N ha^{-1}) left the farm after harvest. In addition, most fruit N uptake resulted in >50% (112 kg N ha^{-1}) capture of N application. Zotarelli et al. (2009a) observed fruit N accumulations of 31.2, 79.3, and 108.2 kg N ha^{-1} in three seasons of tomatoes fertilized with 220 kg N ha^{-1} (14 to 48%). Scholberg et al. (2000) found total N accumulation of well managed tomatoes was 140-200 kg N ha^{-1} with roughly 70% of this amount accumulating in the fruit (98 to 140 kg N ha^{-1}). The sum of our plant N uptake and fruit N uptake accounted for a large amount of the N fertilizer applied (68 to 151%), and in many treatments, resulted in a NUE greater than 100%. This high NUE suggests an additional source of N might be contributing to the system. Irrigation water was tested for inorganic N and resulted in approximately 0.036 mg N L^{-1} NO_3-N and 0.43 mg N L^{-1} NH_3-N. Applications of 1.0ET at peak season (58370 L ha^{-1} day^{-1}), irrigation water was applying 0.002 kg N ha^{-1} day^{-1} NO_3-N and 0.025 kg N ha^{-1} day^{-1} NH_3-N (~0.10 kg NO_3-N ha^{-1} and 1.20 kg NH_3-N ha^{-1} over the growing season). An additional possible N contribution to the system is high levels of N in the groundwater. Samples collected in shallow wells (~1.2 m depth) in April and May, 2012, contained NO_3-N concentrations ~20 mg NO_3-N L^{-1}.

2.4.6. Soil Samples

There were no significant differences in total soil N between treatments at any depth for Spring 2009, Spring 2010, Fall 2010, and Spring 2011 (Appendix, Table 6.8). In Fall 2009, there were significant differences in total soil N in the 0.00-0.25 m depth soil samples. Treatment 0.5ET had significantly more g N kg $soil^{-1}$ than most other treatments, while treatments 0.0ET, 1.0ET, and 1.5ET were significantly lower than most other treatments; which was similar to yield response. In Fall 2009, there were no significant differences in total soil N in the other depths. In Fall 2011, there were significant differences in total soil N in the 0.25-0.50 m depth soil samples. Treatments 1.5ET and Tens60 were significantly higher than other treatments, while treatments 0.0ET and Tens20 were significantly lower than other treatments. In Fall 2011, there were no significant differences in the other depths.

Most soil N is found in non-available plant forms in the soil system with plant available inorganic N accounting for only about 1% (Brady and Weil, 1996). An average concentration of 0.50 g N kg soil^{-1} equates to approximately 1120 kg N ha^{-1} in the top 15 cm ha furrow slice. Determining total soil N provides an estimate of N that has the propensity to mineralize to an inorganic form. We applied inorganic fertilizer at a rate of 224 kg N ha^{-1}, but irrigation generally did not impact total soil N concentrations by the end of the growing season.

The majority of significant differences between treatments for nitrate-N (NO_3-N) (Table 2.3) were seen at shallow sample depths (0.00-0.25 m). Significant differences between treatments in Spring 2009 were only seen at 0.50-0.75 m depth, where 1.5ET had significantly greater concentrations of NO_3-N than 0.5ET and 1.0ET. There were no significant differences between treatments at the three sampled depths in Fall 2009. In the unseasonably warm and dry season of Spring 2010, there were significant differences between treatments in all sampled depths. At 0.00-0.25 and 0.25-0.50 m depths, 0.0ET had higher concentrations of NO_3-N compared to other calculated irrigation treatments. Tens60, the least irrigated tensiometer treatment, was similar in NO_3-N concentration to 0.0ET at 0.00-0.25 m depth, and contained higher concentrations of NO_3-N at 0.50-0.75 m than other treatments in Spring 2010. Being such a hot and dry season, we speculate there was not enough water applied to treatments 0.0ET and Tens60 to optimize yields (Table 2.1), and therefore, residual NO_3-N was higher in those treatments. In Fall 2010, significant differences between treatments were observed to 0.50 m. As seen in Spring 2010, 0.0ET contained significantly more soil NO_3-N than other treatments;

however, yield was not significantly different between treatments in Fall 2010. In Spring 2011, and Fall 2011, there were significant differences between treatments in the shallow sampled depth (0.00-0.25 m), however, there were no differences at the lower depths (0.25-0.50 and 0.50-0.75 m). Generally, as seen in Spring 2010, 0.0ET had more soil NO_3-N than other treatments, and was statistically similar to 0.5ET in Spring 2011 and Fall 2011. A trend of less soil NO_3-N in 0.5ET versus 0.0ET was seen in Fall 2009, Spring 2010, Fall 2010, and Fall 2011. The numerically lower concentrations of residual soil NO_3-N in 0.5ET versus 0.0ET follows numeric yield increases between the treatments in Fall 2009, Spring 2010, and Fall 2010. This observation was also seen in Locascio and Smajstrla (1996) who observed higher inorganic N (NO_3-N + NH_4-N) (0-15 cm) (20 and 80 mg N kg^{-1}) in a 0-water treatment compared to all other irrigated treatments (0.25ET to 1.0ET) (<10 mg N kg^{-1}) including a tensiometer treatment in 2 growing seasons; additionally, the irrigated treatments resulted in significantly greater marketable yields. A residual concentration of 10 mg NO_3-N kg $soil^{-1}$ equates to approximately 22.4 kg NO_3-N ha^{-1} in 15 cm of soil. Concentrations up to 13.4 mg NO_3-N kg $soil^{-1}$ were found in the Tens60 treatment. The residual soil NO_3-N has a high probability of leaching from the sandy textured soils when the polyethylene mulch is removed after the growing season if a cover crop is not implemented.

Higher calculated irrigation rates did not significantly impact residual soil NO_3-N concentrations. 1.0ET, 1.5ET, and 2.0ET generally had statistically similar inorganic N concentrations in all seasons at each depth (except Spring 2010). The lack of significant differences mirrors yield responses for most seasons; no significant differences were observed in yield between 1.0ET, 1.5ET, and 2.0ET in all seasons except Spring 2009 and Spring 2010.

2.4.7. Lysimeters

In all growing seasons, inconsistent data were obtained using suction cup lysimeters. Sample collection greatly varied every week when collection was attempted. In all seasons, on most collection dates, less than 50% of installed lysimeters provided a sample. Samples that were collected were not consistently from the same treatments (i.e. high irrigation treatments). Additionally, water samples ranged in size from approximately 2 mL to >250 mL. Moreover, Fall 2010, produced no samples.

Many revisions were made to lysimeter construction, installation, and backfill material over this study; however, no progress was made in obtaining consistent samples. Suction cup lysimeters have been used in Florida with success on >97% sands with drip irrigation (Zotarelli et al., 2007). We believe the difference in matric potential in a sandy loam soil on the Eastern Shore of Virginia makes suction cup lysimeters less reliable; sandy loam soils hold water more tightly than 97% sands

Due to the lack of consistency in collection, water sample analysis for NO_3-N and NH_3-N was averaged across all treatments for each growing season (Table 2.4). Statistical analysis was not performed, and values are meant to be for informational purposes only. Nitrate-N averages ranged from 12.80 to 40.83 mg NO_3-N L^{-1}. Ammonia-N averages ranged from 0.39 to 1.06 mg NH_3-N L^{-1}. The EPA's maximum contaminant level in drinking water for nitrate is 10 mg L^{-1} (Environmental Protection Agency, 2012). Our nitrate-N concentrations fall above this 10 mg L^{-1} contaminant level and warrant further investigation of possible water contaminants from tomato production systems.

2.5. Conclusions

Yield generally indicated that treatment 0.5ET was the appropriate calculated irrigation regime for optimum yields with minimal irrigation inputs. Treatment Tens40 also provided sufficient irrigation for optimum yields. Soil data at 0.00-0.25 m generally mirrored yield; greater yields resulted in less residual soil NO_3-N. All treatments provided sufficient N to plants according to plant status measurements. The use of a tensiometer set at -40 kPa as a real-time field measurement is an advantageous instrument in unseasonably warm and dry growing seasons, and can protect plants from less than adequate irrigation rates that may decrease yields.

2.6. Acknowledgements

We would like to thank the funders of this project, Virginia Department of Agriculture Specialty Crop Competitive Grant Program, for helping to make this research possible. We would also like to thank the staff at the Virginia Tech Eastern Shore AREC in Painter, Virginia, for their help, hard work, and dedication to this project.

2.7. References

Ahmed, M., M.L. Sharma, Q.D. Richards, and M.S. Al-Kalbani. 2001. Sampling soil water in sandy soils: Comparative analysis of some common methods. Commun. Soil Sci. Plant Anal. 32:1677-1686.

Allen, R., L. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - guidelines for computing crop water requirements, Irrigation and drainage paper 56, FAO, Rome.

Amayreh, J., and N. Al-Abed. 2005. Developing crop coefficients for field-grown tomato (lycopersicon esculentum mill.) under drip irrigation with black plastic mulch. Agric. Water Manage. 73:247-254.

Angelini, R., and V. Magnifico. 2010. Il pomodoro. Coltura & Cultura, Milano.

Brady, N.C., and R.R. Weil. 1996. Nitrogen and sulfur economy of soils. In: A. Kupchik, editor, The nature and properties of soils. Prentice-Hall, Inc., Upper Sadle River, NJ. p. 400-444.

Bremner, J.M. 1996. Nitrogen - total. In: D.L. Sparks, editor, Methods of soil analysis: Part 3. SSSA and ASA, Madison, WI. p. 1085-1121.

Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. FAO, Rome.

Environmental Protection Agency. 2012. Estimated nitrate concentrations in groundwater used for drinking. USEPA. http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/dataset_groundwater.cfm (accessed 10 Feb. 2013).

Grossmann, J., and P. Udluft. 1991. The extraction of soil-water by the suction cup method - a review. J. Soil Sci. 42:83-93.

Haddadin, S.H., and I. Ghawi. 1983. Effect of plastic mulches on soil water conservation and soil temperature in field grown tomato in the jordan valley. Dirasat 13:25-34.

Hochmuth, G.J. 1994. Plant petiole sap-testing for vegetable crops. Horticultural Sciences Dep., Florida Coop. Ext. Serv., IFAS, University of Florida. http://edis.ifas.ufl.edu/cv004 (accessed 6 Sept. 2012).

Hochmuth, G.J., R.C. Hochmuth, and S.M. Olson. 2012. Polyethylene mulching for early vegetable production in north Florida. Cir805. University of Florida, IFAS, EDIS. http://edis.ifas.ufl.edu/cv213 (accessed 22 Aug. 2012).

Hochmuth, G.J., D.N. Maynard, C. Vavrina, E.A. Hanlon, and E. Simonne. 2004. Plant tissue analysis and interpretation for vegetable crops in Florida, HS964, Hort. Sci. Dep., Florida Cooperative Extension Service, IFAS, University of Florida, Gainesville, FL.

Locascio, S.J. 2005. Management of irrigation for vegetables: Past, present, and future. HortTechnology 15:482-485.

Locascio, S.J., and A.G. Smajstrla. 1996. Water application scheduling by pan evaporation for drip-irrigated tomato. J. Am. Soc. Hortic. Sci. 121:63-68.

Machado, R.M.A., and M.D.G. Oliveira. 2005. Tomato root distribution, yield and fruit quality under different subsurface drip irrigation regimes and depths. Irrig. Sci. 24:15-24.

Mulvaney, R.L. 1996. Nitrogen - inorganic forms. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. SSSA and ASA, Madison, WI. p. 1123-1184.

Oliveira, M.D.G., A.M. Calado, and C.A.M. Portas. 1996. Tomato root distribution under drip irrigation. J. Am. Soc. Hortic. Sci. 121:644-648.

Osborne, S.L. 2007. Determining nitrogen nutrition and yield of canola through existing remote sensing technology. Agric. J. 2 (2):180-184.

Ozores-Hampton, M., E. Simonne, F. Roka, K. Morgan, S. Sargent, C. Snodgrass, et al. 2012. Nitrogen rates effects on the yield, nutritional status, fruit quality, and profitability of tomato grown in the spring with subsurface irrigation. HortScience 47:1129-1135.

Rhodes, J.D., and J.D. Oster. 1986. Solute content. In: A. Klute, editor, Methods of soil analysis. Part 1. ASA and SSSA, Madison, WI.

Scholberg, J., B.L. McNeal, K.J. Boote, J.W. Jones, S.J. Locascio, and S.M. Olson. 2000. Nitrogen stress effects on growth and nitrogen accumulation by field-grown tomato. Agron. J. 92:159-167.

Smajstrla, A.G., B.J. Boman, D.Z. Haman, F.T. Izuno, D.J. Pitts, and F.S. Zazueta. 1997. Basic irrigation scheduling in Florida. Agricultural and Biological Engineering Dep., Florida Coop. Ext. Serv., IFAS, University of Florida.

http://citrusbmp.ifas.ufl.edu/References_Publications/Appendix%201%20-%20References/BUL-249.pdf (accessed 8 Feb. 2013).

Soil Survey Staff, Natural Resources Conservation Service, and United States Department of Agriculture. 2013. Official soil series descriptions. http://soils.usda.gov/technical/classification/osd/index.html (accessed 10 Feb. 2013).

Southeast Regional Climate Center. 2007. Historical climate summaries for Virginia. University of North Carolina at Chapel Hill. http://www.sercc.com/cgi-bin/sercc/cliMAIN.pl?va6475 (accessed 8 Feb. 2013).

Stanley, C.D., and G.A. Clark. 2004. Water requirements for drip-irrigated tomato production in southwest Florida. Soil and Water Science Dep., Florida Coop. Ext. Serv., IFAS, University of Florida. http://edis.ifas.ufl.edu/pdffiles/SS/SS43200.pdf (accessed 8 Feb. 2013).

Ulissi, V., F. Antonucci, P. Benincasa, M. Farneselli, G. Tosti, M. Guiducci, et al. 2011. Nitrogen concentration estimation in tomato leaves by VIS-NIR non-destructive spectroscopy. Sensors 11:6411-6424.

USDA-National Agricultural Statistics Service. 2011. U.S. & all states data - tomatoes. http://www.nass.usda.gov/QuickStats/PullData_US.jsp (accessed 24 July 2012).

USDA - Agricultural Marketing Service. 1991. United States standards for grades of fresh tomatoes. http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050331 (accessed 8 Feb. 2013).

Wilson, H.P., T.P. Kuhar, S.L. Rideout, J.H. Freeman, M.S. Reiter, R.A. Straw, et al. 2012. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Zotarelli, L., M.D. Dukes, J.M. Scholberg, R. Munoz-Carpena, and J. Icerman. 2009a. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96:1247-1258.

Zotarelli, L., J.M. Scholberg, M.D. Dukes, and R. Munoz-Carpena. 2007. Monitoring of nitrate leaching in sandy soils: Comparison of three methods. J. Environ. Qual. 36:953-962.

Zotarelli, L., J.M. Scholberg, M.D. Dukes, R. Munoz-Carpena, and J. Icerman. 2009b. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96:23-34.

Table 2.1. Marketable yield for fresh market tomato grown on a Bojac sandy loam soil in 2009, 2010, and 2011.

	2009		2010		2011	
Treatment	Spring	Fall	Spring	Fall	Spring	Fall
	----------kg marketable fruit ha^{-1}----------					
0.0ET	-	32457 c	2345 f	35838	25634 b	33197
0.5ET	70931 a†	44295 ab	22523 e	40880	62651 a	29848
1.0ET	67943 a	37526 bc	32823 cd	29761	56349 a	27684
1.5ET	49451 b	40527 bc	53971 a	27226	63388 a	29509
2.0ET	-	35731 c	46328 ab	26677	55976 a	25118
Tens20‡	-	-	39104 bc	35350	69712 a	33627
Tens40	-	50048 a	47595 ab	32064	62908 a	26666
Tens60	-	-	30350 de	34897	60605 a	32245
P value	0.0073	0.0241	<0.0001	0.1602	0.0407	0.1848

†Means followed by different letters within a column are significantly different (p<0.10).

‡Tensiometer treatments set at -20, -40, and -60 kPa, respectively.

Table 2.2. Total nitrogen uptake in fruit biomass for fresh market tomato plants grown on a Bojac sandy loam soil in 2009, 2010, and 2011.

	2009		2010		2011	
Treatment	Spring	Fall	Spring	Fall	Spring	Fall
	----------	----------	----------	kg N ha^{-1}	----------	----------
0.0ET	-	126.53 c	53.20 d	116.33	119.43 b	153.33
0.5ET	169.25 a†	162.94 ab	117.66 c	133.76	212.63 a	129.92
1.0ET	159.70 a	129.56 c	140.21 bc	99.09	206.40 a	125.05
1.5ET	112.69 b	137.38 bc	204.09 a	97.77	199.63 a	131.64
2.0ET	-	133.08 bc	187.34 a	93.03	183.85 a	141.48
Tens20‡	-	-	143.22 bc	129.36	231.10 a	160.39
Tens40	-	179.34 a	181.73 a	123.89	224.63 a	130.56
Tens60	-	-	150.65 b	126.14	224.85 a	160.88
P value	0.0157	0.0490	<0.0001	0.1507	0.0499	0.1643

†Means followed by different letters within a column are significantly different (p<0.10).
‡Tensiometer treatments set at -20, -40, and -60 kPa, respectively.

Table 2.3. Nitrate-N concentrations of 2*M* KCl extracted soil sampled at depth after tomato growing season on a Bojac sandy loam soil in 2009, 2010, and 2011.

	2009		2010		2011	
Treatment	Spring	Fall	Spring	Fall	Spring	Fall
	------------------mg NO_3-N kg soil^{-1}------------------					
			0.00 – 0.25 m depth			
0.0ET	-	3.68	12.57 a	9.17 a	6.34 a	6.65 a
0.5ET	0.33	1.85	6.02 bc	4.74 b	6.96 a	4.92 ab
1.0ET	0.29	1.83	10.21 ab	2.28 c	2.31 b	4.06 bc
1.5ET	0.26	0.87	3.94 c	3.83 bc	2.63 b	2.40 cd
2.0ET	-	1.01	2.32 c	3.40 bc	2.16 b	1.83 cd
Tens20‡	-	-	5.14 bc	2.21 c	1.83 b	3.34 bcd
Tens40	-	1.18	9.72 ab	3.72 bc	3.85 b	1.42 d
Tens60	-	-	13.70 a	2.98 bc	3.21 b	5.68 ab
P value	0.9112	0.2682	0.0109	<0.0001	0.0090	0.0143
			0.25 – 0.50 m depth			
0.0ET	-	2.25	9.46 a	3.56 a	3.81	0.79
0.5ET	0.75	1.00	6.05 ab	2.99 ab	3.39	1.59
1.0ET	0.86	0.64	4.27 bc	2.16 c	1.88	1.79
1.5ET	1.10	0.72	1.20 c	2.20 c	3.18	1.46
2.0ET	-	2.30	0.97 c	1.83 c	1.26	1.61
Tens20‡	-	-	3.50 bc	1.93 c	4.77	1.03
Tens40	-	0.70	4.89 bc	2.17 c	4.23	0.57
Tens60	-	-	4.83 bc	2.39 bc	2.53	1.32
P value	0.3602	0.3978	0.0738	0.0168	0.7676	0.1166
			0.50 – 0.75 m depth			
0.0ET	-	1.02	2.76 bc	1.24	1.93	0.55
0.5ET	0.48 b	1.02	2.49 cb	1.29	1.99	0.87
1.0ET	0.57 b	0.78	3.56 ab	1.13	1.58	1.21
1.5ET	1.13 a	0.69	1.08 c	0.92	3.80	0.89
2.0ET	-	0.90	1.27 c	0.91	1.41	0.94
Tens20‡	-	-	1.68 bc	1.19	1.23	0.54
Tens40	-	0.45	1.19 c	1.38	2.52	0.44
Tens60	-	-	4.91 a	1.57	1.17	0.52
P value	0.0360	0.1737	0.0424	0.6563	0.6651	0.3011

† Means followed by different letters within a column within a specific depth are significantly different (p<0.10).

‡ Tensiometer treatments set at -20, -40, and -60 kPa, respectively.

Table 2.4. Ammonium and nitrate concentration averages in water samples collected from suction cup lysimeters installed under fresh market tomato plants grown on a Bojac sandy loam soil in 2009, 2010, and 2011.

	2009		2010		2011	
Analyte	Spring	Fall	Spring	Fall	Spring	Fall
	---mg L^{-1}---					
NO_3-N	40.83	16.87	12.88	-	34.77	12.80
NH_3-N	1.06	0.97	0.87	-	0.45	0.39

3. Nitrogen Rate and Application Method Management on Fresh Market Tomato Grown in the Mid-Atlantic.

3.1. Abstract

Virginia commercial N fertilizer recommendations for fresh market tomatoes need revision to provide more accurate recommendations for current agricultural production systems. Two N application methods (banded and incorporated) × five N rates (0, 112, 224, 336, and 448 kg N ha^{-1}) were applied to polyethylene mulched fresh market tomatoes grown on a sandy loam soil. For all treatments, 50% of total applied N was applied pre-plant and 50% was applied via fertigation. Before polyethylene mulch was laid, the incorporated method involved pre-plant N being incorporated into the bed; the banded method involved 33% pre-plant N being incorporated into the bed and 67% pre-plant N applied in a band on the top of the bed. Marketable yield and plant uptake were measured, and post-harvest soil samples were to determine residual soil NO_3-N. Nitrogen rates for maximum yield ranged from 184 to 219 kg N ha^{-1} for the incorporated method and 200 to 242 kg N ha^{-1} for the banded method. The banded method produced higher yields in 2 seasons, and unlike the incorporated method, did not experience crop loss in a hot and dry season. Residual soil NO_3-N showed no differences between N rates using the banded method at 0.00-0.25 m depth while the incorporated method had higher concentrations. Overall, Virginia commercial N fertilizer recommendations for fresh market tomato should be updated to 200-242 kg N ha^{-1} using the banded method for optimum yields, to prevent crop loss in unseasonable years, and to minimize residual soil NO_3-N after the growing season.

3.2. Introduction

Nitrogen is an important nutrient to manage and monitor in cropping systems because it is needed to produce economical yields and has many loss mechanisms in the environment. Once applied to a crop, possible N fates are influenced by soil type, climate, and management practices (Howarth et al., 2002). Fates include plant uptake and subsequent removal from the system via crop harvest, storage by way of organic N in the soil, losses to the atmosphere via volatilization or denitrification, losses via surface flow, or leaching to ground waters (Howarth et al., 1996; Howarth et al., 2002). Reducing nitrogen losses from the system increases nitrogen use efficiency (NUE), crop production profitability, and subsequently reduces potential negative environmental impacts such as accelerated eutrophication (Boesch et al., 2001; Howarth et al., 2002; Ozores-Hampton et al., 2012).

Nutrient recommendations must be made for specific soil types, climates, and crop varieties. Data needed for development of commercial fertilizer recommendations for fresh market tomatoes grown in Virginia are not available, as production systems have changed drastically in recent years. Fresh market tomato cropping systems now include polyethylene mulch, drip irrigation, fumigation, and hybrid varieties resulting in much higher yields per hectare compared to historical levels. Higher yields require higher inputs (International Plant Nutrition Institute, 2011). For example, the International Plant Nutrition Institute (2011) stated that tomato yields of 90 Mg ha^{-1} resulted in a nutrient uptake of 260 kg N ha^{-1}, and 2.9 kg N removed per Mg of tomatoes. However, Virginia fertilizer recommendations have not progressed with the advancements in production. Past N fertilizer recommendations for Virginia grown fresh market tomatoes have varied (Appendix, Table 6.9). From 2004 to 2007, Virginia Cooperative Extension recommendations were to apply 45 kg N ha^{-1} pre-plant, and three to four applications of 45 kg N ha^{-1} via fertigation, totaling 180 to 224 kg N ha^{-1} over the growing season (Bratsch et al., 2004; Bratsch et al., 2005; Kuhar et al., 2006; Kuhar et al., 2007). In 2008, 2009, and 2010, recommendations were to apply 45 to 50 kg N ha^{-1} pre-plant, and to side dress

45 to 50 kg N ha^{-1}, totaling 90 to 100 kg N ha^{-1} over the growing season for sandy loam and loamy sand soils (Kuhar et al., 2008; Kuhar et al., 2009, 2010). In 2011 and 2012, preliminary data from this study were used to update N fertilization recommendations. These recommendations suggested applying 56 to 95 kg N ha^{-1} pre-plant, and to apply 101 to 140 kg N ha^{-1} through fertigation, gradually increasing fertigation rates with plant growth, totaling 168 to 235 kg N ha^{-1} over the growing season (Wilson et al., 2011; Wilson et al., 2012).

Current Florida total-N recommendations for tomato grown on drip irrigated polyethylene mulched beds is 224 kg N ha^{-1} for deep sands or on soils with a shallow impermeable layer (Olson et al., 2012). Olson et al. (2012) suggested an application of 0 to 78 kg N ha^{-1} pre-plant via broadcasting in the bed area, and application of additional N via fertigation throughout the growing season. Additional recommendations for subsurface irrigated tomatoes included broadcasting 20-25% of N into the bed area and banding the remaining N in grooves 5 to 8 cm deep in the shoulders of the bed. As water moves upward through the bed via capillary forces, the nutrient band slowly dissolves and becomes plant available (Geraldson and Whisenant, 1993; Ozores-Hampton et al., 2012). However, Florida has different soils, irrigation practices, and climates than the Mid-Atlantic. Hochmuth and Hanlon (2000) stated that research in Florida has shown equal yields were possible with less N via fertigation than banded N and seepage irrigation. Research data are not available for the behavior of banded N fertilizer with drip irrigation for fresh market tomato in the Mid-Atlantic region.

Scholberg et al. (2000) analyzed growth and yield of field grown tomato under different N fertilizer rates and management systems throughout Florida. Apparent N fertilizer (ANR) recovery as a fraction of N applied ($ANR = U_F – U_o / N_F$; U_F and U_o are N uptake in the presence and absence of fertilizer, respectively, and N_F is the amount of fertilizer applied) decreased as N rates increased with values for drip-irrigated crops ranging from 36 to 74% recovery. Nitrogen accumulation for well managed crops was 140 to 200 kg N ha^{-1}, with approximately 70% found in the fruit. Additionally, in well-fertilized crops (200-300 kg N ha^{-1}), leaf N concentrations ranged from 55 to 65 mg N g^{-1} during initial growth and 20 to 35 mg N g^{-1} at final harvest (Scholberg et al., 2000).

Zhang et al. (2011) observed processing tomatoes with drip irrigation under a factorial arrangement of treatments of 4 N fertilizer rates (0, 120, 240, and 360 kg N ha^{-1}) and 3 P fertilizer rates (0, 100, and 200 kg P_2O_5 ha^{-1} or 0, 44, and 87 kg P ha^{-1}) on a sandy loam in Ontario, Canada. All P fertilizer and 40% of N fertilizer was broadcast and incorporated into the soil pre-plant. The remaining 60% of N fertilizer was applied via fertigation throughout the growing season. All treatments received the same amount of irrigation. Plant N uptake with maximum yield averaged 268 kg N ha^{-1}. Nitrogen uptake efficiency (ratio of plant N uptake/N supply) and N recovery [(Plant uptake in specific treatment – plant uptake in treatment receiving zero N)/(N application rate for specific treatment) × 100] both decreased with increasing fertilizer N rates. Nitrogen uptake efficiency and N recovery were 0.71 and 51.7%, respectively, at the maximum fruit yield. Post-harvest soil samples showed increases in mineral N concentrations with increases in N fertilizer rates. The majority of residual mineral N was found in the upper 40 cm soil layer (Zhang et al., 2011) which is still within the tomato root zone (Oliveira et al., 1996; Machado and Oliveira, 2005).

Ozores-Hampton et al. (2012) observed multiple N rates (22, 67, 134, 202, 269, 336, 403, and 448 kg N ha^{-1}) applied to fresh market tomatoes grown on polyethylene mulch with subsurface irrigation on a fine sand near Palmetto, Florida. The objectives were to determine a range of N rates that would provide optimum yields and post-harvest quality, and maximum economic returns. Petiole sap NO_3-N readings were taken throughout the growing season. During fruit development (11 weeks after transplant), petiole sap NO_3-N concentrations fell below sufficiency levels at fertilizer rates below 202 kg N ha^{-1} and 403 kg N ha^{-1} for the two independent years of the study, and had positive correlation with marketable yield. The two year study had maximum yields after two harvests (97% of yield) fertilized with 172 and 298 kg N ha^{-1} for 2007 and 2008, respectively. Post-harvest fruit quality was not impacted by N fertilizer rate. In Ozores-Hampton et al. study (2012), N rates that produced maximum yields were nearly identical to the N rates that maximized grower profits.

Locascio et al. (1997) compared effects of N and K application scheduling on tomato yield and leaf tissue analysis on drip irrigated tomatoes on a fine sandy loam and fine sandy soil in Florida. At both sites, a total of 196 kg N ha^{-1} were applied. Pre-plant N was applied at 0%, 40%, or 100%, and the remainder N (100%, 60%, and 0%, respectively) was applied via fertigation in either equal or variable applications. Tomatoes responded best with 40% of total N applied pre-plant on the fine sandy soil. With 40% of total N applied pre-plant, the injection schedule of the additional 60% fertigated N had little impact on yield. Timing of fertigated N did not impact yield.

Locascio et al. (1997) also measured petiole sap NO_3-N concentrations of tomato plants. In-season tests, like petiole sap testing and N*ormalized Difference Vegetation Index* (NDVI) readings, can determine N status in plants and are a way to monitor for deficiencies during the growing season (Hochmuth, 1994; Ulissi et al., 2011). Locascio et al. (1997) determined that petiole sap NO_3-N was a good predictor (high correlation coefficients) of potential tomato yield. Florida research suggested an optimum tomato petiole sap NO_3-N range of 400-600 mg N kg^{-1} when fruit are at 5 cm diameter (Hochmuth, 1994). However, these values are based on results from crops grown with subsurface irrigation and all fertilizer applied pre-plant (Hochmuth, 1994; Locascio et al., 1997). NDVI readings from GreenSeeker® depict in-season N status of plants and correlate to plant biomass, plant N concentrations, and seed yield in plants like wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and canola (*Brassica napus* L.) (Osborne, 2007). Instruments like GreenSeeker® that determine NDVI measure red and near infrared (NIR) light reflected off of the plant. Healthy, greener plants absorb more red light, and therefore produce a higher NDVI reading (Trimble Navigation Limited, 2010). Ulissi et al. (2011) observed readings on processing tomatoes grown on clay loam soil including visible-NIR reading, chlorophyll meter readings via SPAD meter, and petiole sap tests. Ulissi et al. (2011) found that visible-NIR readings were highly correlated to leaf N concentration, and proved to be an useful tool to optimize nutrient use efficiency in low-input systems.

Research is needed for current production practices used in Virginia to provide more accurate recommendations that maintain productivity, optimum yields, and fertilizer use efficiency, while limiting N losses. The objective of this study was to determine an optimal N rate and application method for polyethylene mulched, fumigated, drip irrigated tomatoes grown in the Mid-Atlantic on sandy loam soils. Ideally, the findings will produce maximum yields while minimizing N losses to the environment.

3.3. Materials and Methods

This study was established in the spring season of 2009, 2010, and 2011 (three site years) on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludults) at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, Virginia (37.59°N 75.77°W). Bojac sandy loam has approximately 590 g sand kg soil^{-1}, 300 g silt kg soil^{-}

^{1}, and 110 g clay kg soil^{-1} in the Ap horizon. The soil was conventionally tilled, and 0.2 m raised beds were constructed on 1.8 m centers. In a single pass, beds were fumigated with methyl bromide and chloropicrin (67:33, w:w) at the rate of 336 kg ha^{-1}, and 0.5 mm thick polyethylene mulch and drip tape were applied to the bed. Aqua-Traxx drip tubing (Toro, Riverside, CA 92504) with emitters spaced 30 cm apart and a delivery rate of 5.6 L 100 m^{-1} min^{-1} at 0.55 bar was placed 8 to 10 cm from the bed center. Tomato seedlings (‘BHN602’) were transplanted on 46 cm spacings, resulting in a plant population density of approximately 12,000 plants ha^{-1}. Tomato seedlings were transplanted in single row 12 m plots on May 20, 2009, May 21, 2010, and May 27, 2011. All other production practices, besides N management, were conducted according to Kuhar et al. (2009).

This study was a 4 N rate × 2 N application method factorial arrangement plus a 0-N control, for 9 total treatments. The control treatment received no N fertilizer for the duration of the study. All other treatments had 50% of the total N rate applied pre-plant via granular ammonium nitrate (340 g N kg fertilizer^{-1}), under the polyethylene mulch, and 50% applied through fertigation via liquid urea-ammonium nitrate (320 g N kg fertilizer^{-1}) throughout the growing season. Pre-plant N was applied using two methods: a banded method (Figure 3.1) and an incorporated method (Figure 3.2). The banded method received 16.7% total N (33% pre-plant N) by ammonium nitrate being incorporated into the bed using a rototiller, and 33.3% total N (67% pre-plant N) applied as an ammonium nitrate band on the top of the bed located halfway between the drip tape and edge of the plant bed (Figure 3.1). The incorporated method received 50% of the total N rate (100% pre-plant N) by ammonium nitrate being incorporated into the bed using a rototiller (Figure 3.2). Both application methods consisted of four total N rate applications of 112, 224, 336, and 448 kg N hectare^{-1}. Therefore, 56, 112, 168, and 224 kg N hectare^{-1} were applied pre-plant under the polyethylene mulch, and 56, 112, 168, and 224 kg N hectare^{-1} applied via fertigation, respectively (Appendix, Table 6.10). N applied through bi-weekly fertigation increased as the growing season progressed to match plant N uptake (Appendix, Table 6.11) (Wilson et al., 2012).

3.3.1. Lysimeters

A suction cup lysimeter was installed in the center of each plot between two plants to collect soil leachate. Lysimeters consisted of 3.81 cm, schedule 160 PVC pipe (4.82 cm outer diameter) with a 5 cm in length porous ceramic cup (Item No. 0653X01-B01M3, Soilmoisture Equipment Corp., Santa Barbara, CA) affixed to the bottom of the PVC pipe with epoxy. A removable stopper fitting for the top consisted of a polyethylene tube that extended from the bottom interior of the lysimeter cup, up through a size 10 black rubber stopper seated in the PVC pipe. A flexible rubber tube was fitted over the polyethylene tube above the stopper and secured by a stainless steel worm gear hose clamp. Lysimeters were installed with the bottom of the ceramic cup at a 50 cm depth, below the effective tomato root zone (Oliveira et al., 1996; Machado and Oliveira, 2005). Installation was completed by augering to the appropriate depth and back-filling around the lysimeter with silica flour slurry (200 mesh, Soilmoisture Equipment Corp., Santa Barbara, CA) (Ahmed et al., 2001).

Once per week, a 40 kPa vacuum was placed on the lysimeter. After the vacuum was created in the lysimeter, the rubber tube was folded over twice and secured to ensure no leaks. After 30 min, lysimeter leachate was collected by releasing the internal vacuum and placing suction on the rubber tube until all leachate was removed into a secondary collection bottle. Samples were acidified to pH<2.0 and refrigerated at 4° C until analysis (Environmental Protection Agency, 1993c, 1993a, 1993b). Leachate samples were analyzed for ammonium-N

(Mulvaney, 1996) and nitrate-N+nitrite-N (Mulvaney, 1996) colormetrically using Lachat QuickChem 8500 (Hach Company, Loveland, CO 80538).

3.3.2. Nitrogen Status Measurements

Petiole sap nitrate-N tests and NDVI readings were performed when fruit was approximately 5 cm in diameter. Petioles were collected from 6 plants per plot from the upper most fully expanded leaf (Hochmuth, 1994; Ozores-Hampton et al., 2012). The sap of all six petioles was combined and nitrate concentrations (NO_3^--N) were measured using a Cardy meter (Spectrum Technologies, Plainfield, Illinois 60585). A handheld GreenSeeker® (Model 505, NTech Industries, Ukiah, CA 95482) was used to determine NDVI readings. The GreenSeeker® collected data from the entire length of the plot at 30 cm distance from the sides of the plants. Readings taken from the top of the row would have confounding results from string, stakes, et cetera.

3.3.3. Yield

Yield was calculated by harvesting mature green fruit two to three times, depending on the season and fruit production, which is the standard agronomic practice. Fruit was separated by size according to USDA standards (USDA - Agricultural Marketing Service, 1991) and weighed. A small size designation has a minimum diameter of 5.40 cm and a maximum diameter of 5.79 cm, medium (5.72-6.43 cm), large (6.35-7.06 cm), and extra large (>6.99 cm). Culls (unmarketable, blemished fruit) were included with the small fruit size and labeled as unmarketable. Medium, Large, and Extra-Large fruit weights were combined to determine total marketable yield.

3.3.4. Post-Harvest Sampling

After plants were harvested, plant, fruit, and soil samples were collected. One plant per plot was collected, dried at 55°C, and weighed to estimate total above-ground biomass. Plant samples were ground and analyzed for total N via combustion (vario EL cube, Elementar, Elementar Americas, Inc., Mt. Laurel, NJ 08054) to determine plant N concentrations (Bremner, 1996). Five fruit from each plot were collected, dried, ground, and analyzed for total N via combustion to determine fruit N concentration. Plant N concentrations multiplied by total above-ground biomass and total fruit yield determined total plant N uptake.

Soil samples from 0.00-0.25 m, 0.25-0.50 m, and 0.50-0.75 m depths were collected. For each depth, two cores were taken on the side of the bed opposite of the drip tape, and four cores on the side of the bed with the drip tape; two between the drip tape and the edge of the bed and two between the drip tape and the center of the bed. Soil samples were air dried and ground. Soil analysis consisted of total N via combustion (Bremner, 1996) (vario EL cube, Elementar, Elementar Americas, Inc., Mt. Laurel, NJ 08054) and KCl soil extracts. Soil was extracted with 2 *M* KCl at a 1:10 soil:2 *M* KCl ratio, shaken for 1 h, and filtered (Mulvaney, 1996). Extracts were analyzed within 24 hours for ammonium-N and nitrate-N+nitrite-N colormetrically using a Lachat QuickChem 8500 continuous flow analyzer (Mulvaney, 1996) (Hach Company, Loveland, CO 80538).

3.3.5. Statistics

The overall experimental design was a factorial arrangement of 4 N rates × 2 N application methods and a 0-N control in a randomized complete block design that had treatments replicated four times, giving a total plot combination of 36 plots. Statistical analysis was conducted in JMP (JMP, Version 9. SAS Institute Inc., Cary, NC, 2010). Analysis was conducted to determine if year was significant. If year was significant, data were analyzed by year. If year was not significant, data were combined and analyzed over years. Means were separated using Fisher's Protected Lease Significant Difference (LSD) at *alpha* = 0.10. For continuous variables, such as N rate, regression analyses were conducted on data to find peak N rates for production (*alpha* = 0.10).

3.4. Results and Discussion

3.4.1. Yield

Regression analyses were conducted for each application method in 2009, 2010, and 2011 to determine a predictive model for N rate providing optimum yields. In 2009 (Table 3.1), marketable yield followed a negative quadratic function for both application methods; the banded method produced the greatest yield (73354 kg marketable fruit ha^{-1}) by applying 242 kg N ha^{-1}, with an agronomic efficiency (peak kg marketable fruit ha^{-1} / peak kg N ha^{-1}) of 303 kg marketable fruit kg N^{-1}. In 2009, the incorporated method produced the highest yield (70792 kg marketable fruit ha^{-1}) by applying 184 kg N ha^{-1} with an agronomic efficiency of 385 kg marketable fruit kg N^{-1}. The yield responses for the two methods were significantly different (P = 0.0899). A N application rate of 242 kg N ha^{-1} via the banded method had greater yield than the incorporated method.

In 2010 (Table 3.1), marketable yield followed a negative quadratic function using the incorporated method where greatest yield (18977 kg marketable fruit ha^{-1}) was obtained by applying 40 kg N ha^{-1} with an agronomic efficiency of 474 kg marketable fruit kg N^{-1}.. The banded method did not produce a significant yield response; however, the yield response was reported for informational purposes (P = 0.3708). The incorporated method experienced increased plant injury as N rates increased resulting in 79, 45, 31, and 11% plant survival [(alive plants/total plants transplanted) × 100] at N rates of 112, 224, 336, and 448 kg N ha^{-1}, respectively in 2010. Plant injury resulted in small, stunted, and/or brown colored stems and leaves on plants. Residual inorganic soil N (NH_3-N + NO_3-N) concentrations (Appendix, Table 6.12) show significantly higher inorganic N concentrations at the two highest N rates in 2010 (336 and 448 kg N-incorporated versus 224 and 112 kg N-incorporated), averaged over depth. Inorganic N concentrations of soil in 2010 at 0.00-0.25, 0.25-0.50, and 0.50-0.75 m depths for at N rates of 336 and 448 kg N ha^{-1} were 24.9 and 23.1, 8.5 and 10.6, and 10.4 and 10.1 mg N kg^{-1}, respectively. Additionally, 2010 was unseasonably warm accompanied by a severe drought in the beginning of the growing season. Soil temperatures under the black polyethylene mulch reached 60°C, which likely inhibited root growth and plant development (Maynard and Hochmuth, 2007). We hypothesize the high temperatures and high N rates via the incorporated method caused injury to the plants, reducing yields, and resulted in increased inorganic soil N concentrations at 336 and 448 kg N-incorporated. The incorporated method resulted in severe plant injury in an unseasonably warm and dry season, suggesting that even though there was not a significant yield response, the banded method would be a superior application method in warm and dry years by reducing fertilizer injury.

In 2011 (Table 3.1), marketable yield followed a negative quadratic function for both application methods, with peak yield observed at 200 and 219 kg N ha^{-1} for the banded and incorporated method, respectively. The banded method produced the highest yield (56205 kg marketable fruit ha^{-1}) by applying 200 kg N ha^{-1} with an agronomic efficiency of 281 kg marketable fruit kg N^{-1}. The incorporated method produced the highest yields (56458 kg marketable fruit ha^{-1}) using 219 kg N ha^{-1} with an agronomic efficiency of 258 kg marketable fruit kg N^{-1}. Yield response curves for the banded and incorporated methods were statistically different ($P = 0.0025$).

Commercial recommendations in Virginia have traditionally recommended incorporating pre-plant fertilizer in the bed area (Kuhar et al., 2010). The banded method has traditionally been used in Florida in seepage irrigation systems (Olson et al., 2012); as the water table rises, the wetting front slowly dissolves the fertilizer band in the bed, making fertilizer plant available. Commercial growers have adopted this banded method in Virginia in conjunction with drip irrigation by placing the fertilizer band on the top of the bed to dissolve with the wetting front from the drip emitters. Updating Virginia recommendations to accommodate for practices local commercial growers are using is environmentally and economically important.

We observed that the banded method produced higher marketable yields than the incorporated method at a N rate of 242 kg N ha^{-1} in 2009. Additionally, the banded method did not experience crop loss in an unseasonable hot and dry season compared to the same N rates using the incorporated method in 2010. In 2011, yield responses resulted in an additional 253 kg fruit ha^{-1} with 19 kg N ha^{-1} less N applied using the incorporated method. Although the regression equations for banded and incorporated methods were significantly different in 2011, a difference in maximum yield of 253 kg fruit ha^{-1} is negligible (<0.5%). A study by Karlen et al. (1985) observed that applications of 130 and 220 kg N ha^{-1} significantly increased yields compared to 67 kg N ha^{-1}, which has similar rates to our study; however, unlike our study, the authors did not observe differences in marketable yield comparing incorporation and banding methods. We believe the use of the banded method displays the most potential for protecting against crop loss in unseasonably hot and dry periods while also providing optimum yields.

Overall, Virginia Cooperative Extension recommendations should be updated for fresh market polyethylene mulched tomato production systems from a total of 90 to 100 kg N ha^{-1} via a combination of incorporation of 45-50 kg N ha^{-1} pre-plant and side dress of an additional 45-50 kg N ha^{-1} (Kuhar et al., 2010) to a total N recommendation of 200 to 242 kg N ha^{-1} via 100-121 kg N ha^{-1} using the banded application method and fertigation of an additional 100-121 kg N ha^{-1}; which provides highest yields and reduces potential for plant injury.

3.4.2. Petiole Sap Nitrate-N

Petiole sap NO_3-N concentrations were not statistically different by year. Therefore, data were averaged over years (Table 3.2). The 0-N control resulted in the lowest petiole sap NO_3-N concentration and fell below the accepted sufficiency range of 400-600 mg NO_3-N kg^{-1} (Hochmuth, 1994). At 112 kg N ha^{-1}, both methods produced statistically similar petiole sap NO_3-N concentrations. Although petiole sap NO_3-N concentrations at a N rate of 112 kg N ha^{-1} were lower than all higher application rate treatments, the incorporated method fell within the accepted sufficiency range, and the banded method was above the accepted sufficiency range. Application of 448 kg N ha^{-1} via the incorporated method resulted in the highest petiole sap NO_3-N concentration (1218 mg NO_3-N kg^{-1}).

Published guidelines for petiole sap testing in tomato (Hochmuth, 1994) were based on Florida-grown crops with subsurface irrigation and all fertilizer applied pre-plant (Locascio et al., 1997). By continually applying fertilizer via fertigation throughout the growing season, petiole sap concentrations might differ from the accepted published guidelines (Hochmuth, 1994). This was apparent in our petiole sap NO_3-N observations, as all rates above 0-N were within and mostly above the listed tomato petiole sap NO_3-N sufficiency range of 400 to 600 mg

NO_3-N kg^{-1} at 5 cm diameter fruit (Hochmuth, 1994) while yield data suggested we were benefitting from N fertilizer additions via yield increases.

Plotting petiole sap NO_3-N concentrations against the corresponding marketable yield produced a significant (P = 0.0014) quadratic response in 2009 (Appendix, Figure 6.1). Peak yield was produced at a petiole sap NO_3-N concentration of 835 mg NO_3-N kg^{-1}. Preliminary data suggests a 10% confidence interval of 751 – 919 mg NO_3-N kg^{-1} would predict peak marketable yields for fresh market tomato grown on polyethylene mulch in Virginia. The range of 751 – 919 mg NO_3-N kg^{-1} encompasses the petiole sap nitrate-N concentrations found in treatments receiving 224 kg N ha^{-1} using both the incorporated and banded method (Table 3.2). Virginia soils, climate, and production practices require higher petiole sap NO_3-N readings than the currently accepted 400-600 mg NO_3-N kg^{-1} reported by Hochmuth (1994) and warrants further investigation of optimum petiole sap NO_3-N readings for current practices used in Virginia.

3.4.3. NDVI

Although significant functions were found with NDVI measurements (Appendix, Table 6.13), overall, NDVI did not produce consistent response curves for either method or N rate. Difficulties in obtaining consistent NDVI data for fresh market tomatoes are likely due to production practices. Fresh market tomato plants are staked and strung to keep plants vertical. By doing so, both the darker green upper side and lighter green underside of the leaves are often exposed on the sides of the plant where NDVI readings were taken. Additionally, readings were performed when small immature green fruit were present. The multiple shades of green from the upper side and underside of leaves, and fruit present likely confounded results. Ulissi et al. (2011) found a chlorophyll meter reading (SPAD) to be a useful tool in low input processing tomato production models; however, the SPAD meter clips directly onto the plant leaf. Therefore, fruit color, stakes, string, and other variables do not interfere with data when using SPAD meters.

3.4.4. Plant Nitrogen Concentrations

Plant N concentrations (Appendix, Table 6.14) followed significant quadratic functions for both methods in 2009, 2010, and 2011. Plant N concentration responses generally increased with increasing N rates used in this study. Average plant N concentrations ranged from 16.24 to 36.42 g N kg^{-1} over the duration of the study. According to standard values for tissue analysis for Florida (Hochmuth et al., 2004), our plant tissue analysis tested mainly in adequate (20 to 30 g N kg^{-1}) and high (>30 g N kg^{-1}) status levels for harvest period sampling. Overall, all fertilized treatments had higher than 20 g N kg^{-1}, which differs from Florida's "adequate" range; as we saw yield response to more N applied.

Plant N uptake (Table 3.3) was not significant by year; therefore, data were averaged over year, and a least significant difference value ($LSD_{0.10}$) was calculated. Plant N uptake (Table 3.3) resulted in treatments 448 kg N-banded, 112 kg N-banded, and 336 kg N-incorporated producing statistically similar plant N uptake rates (92.61, 80.10, and 78.50 kg N ha^{-1}, respectively). The 0-N control resulted in the lowest plant N uptake (36.14 kg N ha^{-1}), and was statistically similar to treatment 112 kg N-incorporated (50.32 kg N ha^{-1}). Scholberg et al. (2000) found that at the end of the growing season, 39% of total N uptake was found in the leaves and stems of unstressed tomato plant. Calculations (plant N uptake/total N uptake × 100) show applying 224 kg N-banded resulted in 28%, 45%, and 38% of total N uptake found in the leaves and stems of the tomato plant in our study for 2009, 2010, and 2011, respectively.

Total N uptake for the system (plant N uptake + fruit N uptake) (Table 3.4) showed significant quadratic responses for both methods in 2009 and 2011 and differed by year. No significant response was found in 2010. The calculated maximum of total N uptake of the banded method responses showed that applying 258 and 248 kg N ha^{-1} in 2009 and 2011, respectively, produced the greatest total N uptake. The maximum total N uptake of the incorporated method responses showed that applying 200 and 268 kg N ha^{-1} in 2009 and 2011, respectively, produced the greatest total N uptake. Zhang et al. (2011) warns against N applications in excess of what is required for maximum yields due to luxury consumption by the vegetative portion of the plant. Highest yields used 200 to 242 kg N ha^{-1} and demonstrate that updating Virginia N fertilizer recommendations will provide adequate N for maximum N uptake and yield.

The 0-N control resulted in 36.14 kg N ha^{-1} of plant N uptake (Table 3.3) and from 82.96 to 172.22 kg N ha^{-1} total N uptake (Table 3.4) during the study. Zhang et al. (2011) also found high total N uptake in the 0-N controls of their study in Ontario, Canada (198, 97, and 89 kg N ha^{-1}). Possible N sources in the 0-N control were N in the groundwater, irrigation water, precipitation, and mineralization of soil organic matter. Soil samples (0.00-0.50 m) taken from the control plots resulted in moderate-low N mineralization potential (will not provide sufficient N for most crops) from a Haney-Brinton Solvita test (Franzluebbers et al., 1996; Haney and Haney, 2010). Results showed CO_2-C levels of 16 mg kg^{-1} and this concentration estimates a contribution of approximately 9 kg N ha^{-1} via mineralization over the growing season. Irrigation water was tested for inorganic N and contained 0.036 mg N L^{-1} NO_3-N and 0.43 mg N L^{-1} NH_3-N. Applications of irrigation at peak season (58370 L ha^{-1} day^{-1}), irrigation water was applying 0.002 kg N ha^{-1} day^{-1} NO_3-N and 0.025 kg N ha^{-1} day^{-1} NH_3-N (~0.10 kg NO_3-N ha^{-1} and 1.20 kg NH_3-N ha^{-1} over the growing season). Atmospheric wet deposition of NH_4 + NO_3 according to the National Atmospheric Deposition Program (2012) totaled 6.89, 3.97, and 8.41 kg ha^{-1} during the spring and summer seasons in 2009, 2010, and 2011, respectively for nearby Smith Island, MD. An additional possible N contribution to the system was high levels of N in the groundwater. Samples collected in shallow wells (~1.2 m depth) in April and May, 2012, contained NO_3-N concentrations ~20 mg NO_3-N L^{-1}. Overall, approximately 15 kg N ha^{-1} plus groundwater contribution was available from environmental sources.

Percent N recovered [(Total N uptake)-(0-N control total N uptake)/(Total N applied)×100] (Table 3.5) was over 55% for 2009, 2010, and 2011, applying a rate of 112 kg N ha^{-1} using both application methods. Except for the incorporated method in 2010 (where substantial plant injury occurred in higher N rates), percent N recovered was over 35% for 2009, 2010, and 2011 applying a rate of 224 kg N ha^{-1}. Overall, a trend of decreasing N recovery with increasing N rate, as seen in this study, has been seen in previous studies (Scholberg et al., 2000; Zotarelli et al., 2009; Zhang et al., 2011). Scholberg et al. (2000) saw N recovery from 74 to 34% as N rate increased from 66 to 166 kg N ha^{-1}. Zhang et al. (2011) observed N recovery from 84 to 28% as N rate increased from 120 to 360 kg N ha^{-1}. Raun and Johnson (1999) reported the world cereal grain NUE to be 33% (NUE = [(total cereal N removes) – (N coming from the soil + N deposited in rainfall)]/(fertilizer N applied to cereals)). Overall, the recovery percentage for N rates up to 224 kg N ha^{-1} are higher than cited by Raun and Johnson (1999) for cereal crops and are consistent with other vegetable studies, meaning that Virginia Cooperative Extension recommendations for fresh market polyethylene mulch tomato production systems of 200 to 242 kg N ha^{-1} would generally fall within observed N recovery.

3.4.5. Soil Nitrogen Concentrations

Generally, results for total soil N concentrations showed no significant differences between the banded and incorporated method by year (Appendix, Table 6.15) or at depth (Appendix, Table 6.16). However, concentrations of total soil N were greater at the shallow depth (0.00-0.25 m) versus deeper depths (Table 3.6). Most soil N is found in non-available plant forms in the soil system with plant available inorganic N accounting for only about 1% (Brady and Weil, 1996). A concentration of 0.50 g N kg soil^{-1} equates to approximately 1120 kg N ha^{-1} in the top 15 cm ha furrow slice. Determining total soil N provides an estimate of N that has the propensity to mineralize to an inorganic, plant available form. We found that application method and N rate did not seem to impact total soil N, except for applications above agronomic needs (448 kg-incorporated; Table 3.7). However, with higher concentrations of total soil N at the shallow depth (0.00-0.25 m), more N could mineralize into plant available forms of N from organic matter in the plant's root zone (0.00-0.40 m) (Oliveira et al., 1996; Machado and Oliveira, 2005).

Residual inorganic soil NO_3-N showed several significant interactions including: year×method×rate (Table 3.8), and depth×method×rate (Table 3.9). The interaction of year×method×rate (Table 3.8) showed the highest residual NO_3-N using 448 kg-incorporated in 2011, averaged over depth. Additionally, in 2010, 448 kg- and 336 kg-incorporated resulted in significantly higher residual soil NO_3-N than 224 kg- and 112 kg-incorporated, which mirrored low yield from fertilizer injury (Table 3.1) at the higher N rates using the incorporated method in 2010. The interaction of depth×method×rate, averaged over years (Table 3.9) resulted in treatment 448 kg-incorporated at shallow depth (0.00-0.25 m) having significantly higher residual NO_3-N than any other treatment at all depths. This is likely due to over-application of N and crop loss at higher incorporated rates which mirrors yield response (Table 3.1) and excess available N fertilizer. In general, as expected, residual NO_3-N generally increased with increasing N rates at 0.00-0.25 and 0.25-0.50 m depths. Very few differences were found comparing treatments at 0.50-0.75 m, indicating little leaching of fertilizer during the time of this study.

Residual nitrate is prone to leaching after polyethylene mulch is removed from the soil and is directly exposed to precipitation. A concentration of 5.0 mg N kg soil^{-1} equates to approximately 11.2 kg N ha^{-1} in the top 15 cm ha furrow slice. Applying 448 kg-incorporated left behind 16.89 mg NO_3-N kg soil^{-1}, resulting in 38 kg NO_3-N ha^{-1} left in the soil surface. This residual N is an economic loss and a possible environmental stressor (Boesch et al., 2001; Howarth et al., 2002; Ozores-Hampton et al., 2012). Zotarelli et al. (2007) found that nitrate in soil cores from tomatoes grown under a time-fixed irrigation schedule was significantly greater in plots receiving 312 kg N ha^{-1} versus 208 kg N ha^{-1} which is similar to our data. Zhang et al. (2011) saw residual inorganic N from 0-100 cm increase at N rates above those required for maximum tomato yield (especially at 360 kg N ha^{-1}) as well. Our study showed that applying 336 kg N or more via the incorporated method will significantly increase residual NO_3-N in topsoil versus applying 112 and 224 kg N-incorporated (Table 3.9). However, no significant differences were seen between rates using the banded method at 0.00-0.25 m. Additionally, inorganic N concentrations were significantly lower in topsoil by applying 112 kg N-banded, 224 kg N-banded, and 448 kg N banded than applications of 336 kg N or more via the incorporated method (Table 3.9). This suggests N rates that maximize marketable yield (200-242 kg N ha^{-1} via the banded method) will result in minimal residual soil N.

3.4.6. Lysimeters

In all growing seasons, inconsistent data were obtained using suction cup lysimeters. Sample amounts greatly varied every week when collection was attempted. In all seasons, on most collection dates, less than 50% of installed lysimeters provided a sample. Samples that were collected were not consistently from the same treatments. Additionally, water samples ranged in size from approximately 2 mL to >250 mL.

Many revisions were made to lysimeter construction, installation, and backfill material over this study; however, no progress was made in obtaining consistent samples. Suction cup lysimeters have been used in Florida with success on >97% sands with drip irrigation (Zotarelli et al., 2007). We believe the difference in matric potential in a sandy loam soil on the Eastern Shore of Virginia makes suction cup lysimeters less reliable as sandy loam soils hold water more tightly than 97% sands.

Due to the lack of consistency in collection, water sample analysis for NO_3-N and NH_3-N was averaged by treatment for each growing season (Table 3.10). Statistical analysis was not performed, and values are meant to be for informational purposes only. Nitrate-N averages ranged from 8.39 mg NO_3-N L^{-1} (0-N control treatment) to 147.14 mg NO_3-N L^{-1} (448 kg N ha^{-1} treatment, incorporated). Ammonia-N averages ranged from 0.18 to 6.82 mg NH_3-N L^{-1}. The EPA's maximum contaminant level in drinking water for nitrate is 10 mg L^{-1} (Environmental Protection Agency, 2012). Our nitrate-N concentrations fell above this 10 mg L^{-1} contaminant level in all fertilized plots and warrant further investigation of possible water contaminants from tomato production systems.

3.5. Conclusions

Results from yield data indicated that Virginia N fertilizer recommendations for polyethylene mulched fresh market tomatoes should be updated to allow application rates of 200 to 242 kg N ha^{-1}. Of this total amount, 100-121 kg N ha^{-1} should be applied using the banded application method at application of polyethylene mulch and 100-121 kg N ha^{-1} should be applied using fertigation; which provides highest yields and reduces potential for plant injury. These N rates using the banded method will provide acceptable fertilizer recovery, ample petiole sap nitrate-N, and reduce residual inorganic soil N, compared to higher N rates and the incorporated method.

3.6. Acknowledgements

We would like to thank the funders of this project, Virginia Department of Agriculture Specialty Crop Competitive Grant Program, for helping to make this research possible. We would also like to thank the staff at the Virginia Tech Eastern Shore AREC in Painter, Virginia, for their help, hard work, and dedication to this project.

3.7. References

Ahmed, M., M.L. Sharma, Q.D. Richards, and M.S. Al-Kalbani. 2001. Sampling soil water in sandy soils: Comparative analysis of some common methods. Commun. Soil Sci. Plant Anal. 32:1677-1686.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. J. Environ. Qual. 30:303-320.

Brady, N.C., and R.R. Weil. 1996. Nitrogen and sulfur economy of soils. In: A. Kupchik, editor, The nature and properties of soils. Prentice-Hall, Inc., Upper Sadle River, NJ. p. 400-444.

Bratsch, A.D., T.P. Kuhar, S.B. Phillips, S.B. Sterrett, C.M. Waldenmaier, and H.P. Wilson. 2004. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Bratsch, A.D., T.P. Kuhar, S.B. Phillips, S.B. Sterrett, C.M. Waldenmaier, H.P. Wilson, et al. 2005. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Bremner, J.M. 1996. Nitrogen - total. In: D.L. Sparks, editor, Methods of soil analysis: Part 3. SSSA and ASA, Madison, WI. p. 1085-1121.

Environmental Protection Agency. 1993a. Method 350.1, determination of ammonia nitrogen by semi-automated colorimetery, Environmental Monitoring Systems Laboratory, Office of Research and Development, Cincinnati, OH.

Environmental Protection Agency. 1993b. Method 353.2, determination of nitrate-nitrite nitrogen by semi-automated colorimetery, Environmental Monitoring Systems Laboratory, Office of Research and Development, Cincinnati, OH.

Environmental Protection Agency. 1993c. Method 365.1, determination of phosphorus by semi-automated colorimetery, Environmental Monitoring Systems Laboratory, Office of Research and Development, Cincinnati, OH.

Environmental Protection Agency. 2012. Estimated nitrate concentrations in groundwater used for drinking. USEPA. http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/dataset_groundwater.cfm (accessed 10 Feb. 2013).

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Sci. Soc. Am. J. 60:1133-1139.

Geraldson, C.M., and B. Whisenant. 1993. An opinion on the gradient concept of nutrition. 106:201-202.

Haney, R.L., and E.B. Haney. 2010. Simple and rapid laboratory method for rewetting dry soil for incubations. Commun. Soil Sci. Plant Anal. 41:1493-1501.

Hochmuth, G.J. 1994. Plant petiole sap-testing for vegetable crops. Horticultural Sciences Dep., Florida Coop. Ext. Serv., IFAS, University of Florida. http://edis.ifas.ufl.edu/cv004 (accessed 6 Sept. 2012).

Hochmuth, G.J., and E.A. Hanlon. 2000. A summary of N, P, and K research with tomato in Florida. Horticultural Sciences Dep., Florida Coop. Ext. Serv., IFAS, University of Florida. http://edis.ifas.ufl.edu/cv236 (accessed Dec 21 2012).

Hochmuth, G.J., D.N. Maynard, C. Vavrina, E.A. Hanlon, and E. Simonne. 2004. Plant tissue analysis and interpretation for vegetable crops in Florida, HS964, Hort. Sci. Dep., Florida Cooperative Extension Service, IFAS, University of Florida, Gainesville, FL.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, et al. 1996. Regional nitrogen budgets and riverine N&P fluxes for the drainages to the north atlantic ocean: Natural and human influences. Biogeochemistry 35:75-139.

Howarth, R.W., A. Sharpley, and D. Walker. 2002. Sources of nutrient pollution to coastal waters in the United States: Implications for achieving coastal water quality goals. Estuaries 25:656-676.

International Plant Nutrition Institute. 2011. Nutrient uptake and removal for southern crops. IPNI. http://nase.ipni.net/articles/NASE0044-EN (accessed 17 Sept. 2012).

Karlen, D.L., C.R. Camp, and M.L. Robbins. 1985. Fresh-market tomato response to N and K fertilization and water management-practices. Commun. Soil Sci. Plant Anal. 16:71-81.

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2009. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2010. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2008. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, S.B. Phillips, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2007. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., S.B. Phillips, R.A. Straw, C.M. Waldenmaier, and H.P. Wilson. 2006. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Locascio, S.J., G.J. Hochmuth, F.M. Rhoads, S.M. Olson, A.G. Smajstrla, and E.A. Hanlon. 1997. Nitrogen and potassium application scheduling effects on drip-irrigated tomato yield and leaf tissue analysis. Hortscience 32:230-235.

Machado, R.M.A., and M.D.G. Oliveira. 2005. Tomato root distribution, yield and fruit quality under different subsurface drip irrigation regimes and depths. Irrig. Sci. 24:15-24.

Maynard, D.N., and G.J. Hochmuth. 2007. Knott's handbook for vegetable growers. Fifth ed. John Wiley & Sons, Inc., NJ.

Microsoft. 2007. Microsoft clip art, Redmond, WA.

Mulvaney, R.L. 1996. Nitrogen - inorganic forms. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. SSSA and ASA, Madison, WI. p. 1123-1184.

National Atmospheric Deposition Program. 2012. NADP/NTN monitoring location MD15. http://nadp.sws.uiuc.edu/sites/siteinfo.asp?net=NTN&id=MD15 (accessed 14 Feb. 2013).

Oliveira, M.D.G., A.M. Calado, and C.A.M. Portas. 1996. Tomato root distribution under drip irrigation. J. Am. Soc. Hortic. Sci. 121:644-648.

Olson, S.M., P.J. Dittmar, G.E. Vallad, S.E. Webb, S.A. Smith, E.J. McAvoy, et al. 2012. Tomato production in Florida. In: S.M. Olson , and B.M. Santos, editor, Vegetable production handbook for Florida 2012-2013. Vance Publishing Inc., Lenexa, KS. p. 321-344.

Osborne, S.L. 2007. Determining nitrogen nutrition and yield of canola through existing remote sensing technology. Agric. J. 2 (2):180-184.

Ozores-Hampton, M., E. Simonne, F. Roka, K. Morgan, S. Sargent, C. Snodgrass, et al. 2012. Nitrogen rates effects on the yield, nutritional status, fruit quality, and profitability of tomato grown in the spring with subsurface irrigation. HortScience 47:1129-1135.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Scholberg, J., B.L. McNeal, K.J. Boote, J.W. Jones, S.J. Locascio, and S.M. Olson. 2000. Nitrogen stress effects on growth and nitrogen accumulation by field-grown tomato. Agron. J. 92:159-167.

Trimble Navigation Limited. 2010. Greenseeker frequently asked questions. http://www.ntechindustries.com/greenseeker_faqs.html (accessed Dec 22 2012).

Ulissi, V., F. Antonucci, P. Benincasa, M. Farneselli, G. Tosti, M. Guiducci, et al. 2011. Nitrogen concentration estimation in tomato leaves by VIS-NIR non-destructive spectroscopy. Sensors 11:6411-6424.

USDA - Agricultural Marketing Service. 1991. United States standards for grades of fresh tomatoes. http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050331 (accessed 8 Feb. 2013).

Wilson, H.P., T.P. Kuhar, S.L. Rideout, J.H. Freeman, M.S. Reiter, R.A. Straw, et al. 2012. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Wilson, H.P., T.P. Kuhar, S.L. Rideout, J.H. Freeman, M.S. Reiter, R.A. Straw, et al. 2011. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Zhang, T.Q., K. Liu, C.S. Tan, J. Warner, and Y.T. Wang. 2011. Processing tomato nitrogen utilization and soil residual nitrogen as influenced by nitrogen and phosphorus additions with drip-fertigation. Soil Sci. Soc. Am. J. 75:738-745.

Zotarelli, L., M.D. Dukes, J.M. Scholberg, R. Munoz-Carpena, and J. Icerman. 2009. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96:1247-1258.

Zotarelli, L., J.M. Scholberg, M.D. Dukes, and R. Munoz-Carpena. 2007. Monitoring of nitrate leaching in sandy soils: Comparison of three methods. J. Environ. Qual. 36:953-962.

Table 3.1. Marketable yield for fresh market tomato plants grown on polyethylene mulch on a Bojac sandy loam soil during 2009, 2010, and 2011.

Total N rate treatment†	2009 Banded	2009 Incorporated	2010 Banded	2010 Incorporated	2011 Banded	2011 Incorporated
--(kg ha^{-1})--	--------kg marketable fruit ha^{-1}--------					
112	69169	68363	28595	26027	55150	48279
224	70098	72103	21758	10266	51105	52487
336	70396	58870	24990	3029	53171	56492
448	66324	45907	21385	1321	49343	50962
P value‡	<0.0001	0.0003	0.3708	0.0256	0.0095	0.0059
Yield Response§						
Banded	$-0.4268N^2 + 206.76N + 48313$		$-0.2467N^2 + 87.589N + 18027$		$-0.5994N^2 + 239.92N + 32197$	
Incorporated	$-0.6802N^2 + 249.95N + 47830$		$-0.1642N^2 – 13.249N + 19770$		$-0.5544N^2 + 242.33N + 29977$	
P value¶	0.0899		0.3816		0.0025	

†0-N control treatment averaged 46185, 16120, and 29089 kg marketable fruit ha^{-1} in 2009, 2010, and 2011, respectively.
‡*P* value for regression equation.
§Highest order model (linear or quadratic) that was significant presented.
¶P value for Banded versus Incorporated yield response comparison.

Table 3.2. Petiole sap NO_3-N concentrations for fresh market tomato grown on polyethylene mulch on a Bojac sandy loam soil, averaged over years (2009, 2010, and 2011).

Total N rate treatment†	Banded	Incorporated
--(kg ha^{-1})--	-------------------------mg NO_3-N kg^{-1}-------------------------	
112	639 d‡	562 d
224	865 c	992 b
336	1017 b	1042 b
448	1015 b	1218 a
$LSD_{0.10}$	108	

†0-N control treatment averaged 304 mg NO_3-N kg^{-1}.
‡Means followed by different letters are significantly different (p<0.10).

Table 3.3. Plant N uptake for fresh market tomato plants grown on polyethylene mulch on a Bojac sandy loam soil, averaged over years (2009, 2010, and 2011).

Total N rate treatment†	Banded	Incorporated
--(kg ha^{-1})--	--------------------------------- kg N ha^{-1}---------------------------------	
112	80.10 ab‡	50.32 cd
224	72.01 b	65.71 bc
336	69.13 bc	78.50 ab
448	92.61 a	68.12 bc
$LSD_{0.10}$	19.23	

†0-N control treatment averaged 36.14 kg N ha^{-1}.
‡Means followed by different letters are significantly different (p<0.10).

Table 3.4. Total N uptake (plant + fruit) for fresh market tomato plants grown on polyethylene mulch on a Bojac sandy loam soil during 2009, 2010, and 2011.

Total N rate treatment†	2009		2010		2011	
	Banded	Incorporated	Banded	Incorporated	Banded	Incorporated
--(kg ha^{-1})--	---kg N ha^{-1}---					
112	258.93	233.61	171.34	160.97	213.38	173.76
224	253.81	300.16	161.56	115.07	191.47	205.01
336	268.96	240.58	139.71	69.23	197.27	249.72
448	263.58	195.34	184.08	120.49	223.44	230.56
P value‡	0.0045	0.0056	ns§	ns	0.0150	0.0003
N Uptake Response¶						
Banded	$-0.0014x^2 + 0.7216x + 180.93$		ns		$-0.0016x^2 + 0.7927x + 119.84$	
Incorporated	$-0.0026x^2 + 1.0686x + 169.26$		ns		$-0.0019x^2 + 1.0173x + 101.61$	

†0-N control treatment averaged 172.22, 82.96, and 102.09 kg N ha^{-1} in 2009, 2010, and 2011, respectively.
‡P value for regression equation.
§Not significant.
¶Highest order model (linear or quadratic) that was significant presented.

Table 3.5. Percent N recovery of applied fertilizer for fresh market tomato plants grown on polyethylene mulch on a Bojac sandy loam soil during 2009, 2010, and 2011.

Total N rate treatment†	2009		2010		2011	
	Banded	Incorporated	Banded	Incorporated	Banded	Incorporated
--(kg ha^{-1})--	---%---					
112	77†	55	79	70	99	64
224	36	57	35	14	40	46
336	29	20	17	-4	28	44
448	20	5	23	8	27	29

†Yearly average of total N uptake for 0-N control treatment subtracted from each treatment mean before calculating percent recovery.

Table 3.6. Total soil N concentrations sampled after fresh market tomato growing season on a Bojac sandy loam soil in Painter, VA (year × depth interaction) averaged over N rate and method.

Depth	2009†	2010‡	2011§
--------m--------		---------------------g N kg soil^{-1}---------------------	
0.00-0.25	0.52 a¶	0.51 a	0.44 b
0.25-0.50	0.45 b	0.38 c	0.36 c
0.50-0.75	0.29 d	0.25 e	0.27 de
		$LSD_{0.10}$ = 0.02	

†0-N = 0.49, 0.42, and 0.29 g N kg soil^{-1} at 0.00-0.25, 0.25-0.50, and 0.50-0.75 m.
‡0-N = 0.46, 0.34, and 0.25 g N kg soil^{-1} at 0.00-0.25, 0.25-0.50, and 0.50-0.75 m.
§0-N = 0.42, 0.32, and 0.26 g N kg soil^{-1} at 0.00-0.25, 0.25-0.50, and 0.50-0.75 m.
¶Means followed by different letters are significantly different (p<0.10).

Table 3.7. Total soil N concentrations sampled after fresh market tomato growing season on a Bojac sandy loam soil in Painter, VA (method × rate interaction) averaged over years (2009, 2010, and 2011) and depths.

Total N rate treatment †	Banded	Incorporated
------kg ha^{-1}--------	---------------------g N kg soil^{-1}---------------------	
112	0.39 abc‡	0.38 bc
224	0.40 ab	0.37 c
336	0.39 abc	0.38 bc
448	0.38 bc	0.41 a
	$LSD_{0.10}$ = 0.02	

†0-N = 0.36 g N kg soil^{-1}
‡Means followed by different letters are significantly different (p<0.10).

Table 3.8. Nitrate-N concentrations of 2*M* KCl extracted soil sampled after fresh market tomato growing season on a Bojac sandy loam soil (year × method × rate interaction), averaged over depths.

Total N rate treatment†	2009		2010		2011	
	Banded	Incorporated	Banded	Incorporated	Banded	Incorporated
--(kg ha^{-1})--	--- mg NO_3-N kg $soil^{-1}$---					
112	0.81 k‡	0.96 k	3.96 defghij	1.39 jk	2.02 hijk	2.70 fghijk
224	2.07 hijk	2.56 ghijk	1.85 ijk	1.92 ijk	3.92 defghij	5.02 bcdefg
336	3.26 efghijk	4.64 defghi	5.04 bcdefg	7.93 b	6.79 bcd	4.89 cdefgh
448	5.58 bcdef	6.47 bcd	5.70 bcde	7.58 bc	5.03 bcdefg	13.09 a
			$LSD_{0.10}$ = 2.93			

†0-N control treatment averaged 0.85, 3.96, and 1.74 mg NO_3-N kg $soil^{-1}$ in 2009, 2010, and 2011, respectively.
‡Means followed by different letters are significantly different (p<0.10).

Table 3.9. Nitrate-N concentrations of 2*M* KCl extracted soil sampled after fresh market tomato growing season on a Bojac sandy loam soil (depth × method × rate interaction), averaged over years (2009, 2010, and 2011).

Total N rate treatment†	0.00-0.25 m		0.25-0.50 m		0.50-0.75 m	
	Banded	Incorporated	Banded	Incorporated	Banded	Incorporated
--(kg ha^{-1})--	--- mg NO_3-N kg $soil^{-1}$---					
112	4.00 cdefgh‡	1.52 hij	1.05 ij	0.96 j	1.73 ghij	2.57 fghij
224	4.03 cdefgh	4.62 cdefg	1.44 hij	2.66 fghij	2.36 fghij	2.22 fghij
336	6.45 bc	9.30 b	5.70 cde	4.67 cdef	2.95 efghij	3.49 defghij
448	6.16 cd	16.89 a	6.18 cd	6.12 cd	3.97 cdefghi	4.14 cdefgh
			$LSD_{0.10}$ = 2.93			

†0-N control treatment averaged 1.12, 0.59, and 4.84 mg NO_3-N kg $soil^{-1}$ at 0.00-0.25, 0.25-0.50, and 0.50-0.75 m depth, respectively.
‡Means followed by different letters are significantly different (p<0.10).

Table 3.10. Nutrient concentration averages in water samples collected from suction cup lysimeters installed under fresh market tomato plants grown on a Bojac sandy loam soil during 2009, 2010, and 2011.

Total N rate treatment	Method	2009	2010	2011
		NO_3-N		
----kg ha^{-1}----		----------------------	mg L^{-1}	----------------------
0	Control	51.96	8.39	11.36
112	Banded	67.77	15.70	36.40
224	Banded	55.67	28.60	40.64
336	Banded	60.36	22.14	37.38
448	Banded	49.59	66.46	38.79
112	Incorporated	42.45	22.45	18.63
224	Incorporated	70.16	78.83	68.16
336	Incorporated	79.13	115.65	136.61
448	Incorporated	59.60	147.14	130.08
		NH_3-N		
0	Control	0.19	0.42	0.23
112	Banded	0.36	0.68	0.34
224	Banded	0.21	0.83	0.32
336	Banded	1.79	0.18	0.31
448	Banded	0.25	0.56	0.24
112	Incorporated	0.34	0.34	0.30
224	Incorporated	0.78	0.23	0.32
336	Incorporated	0.30	0.26	0.39
448	Incorporated	1.12	6.82	1.13

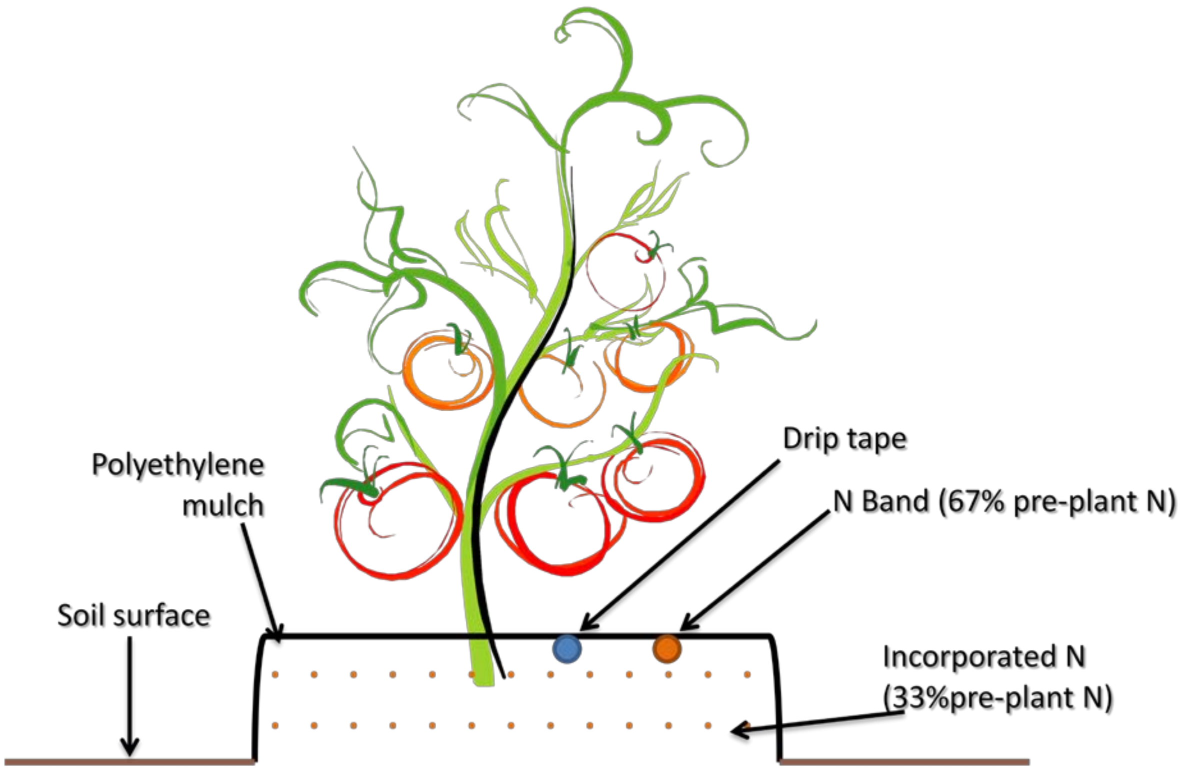

Figure 3.1. Depiction of Banded method of fertilizer placement (Microsoft, 2007).

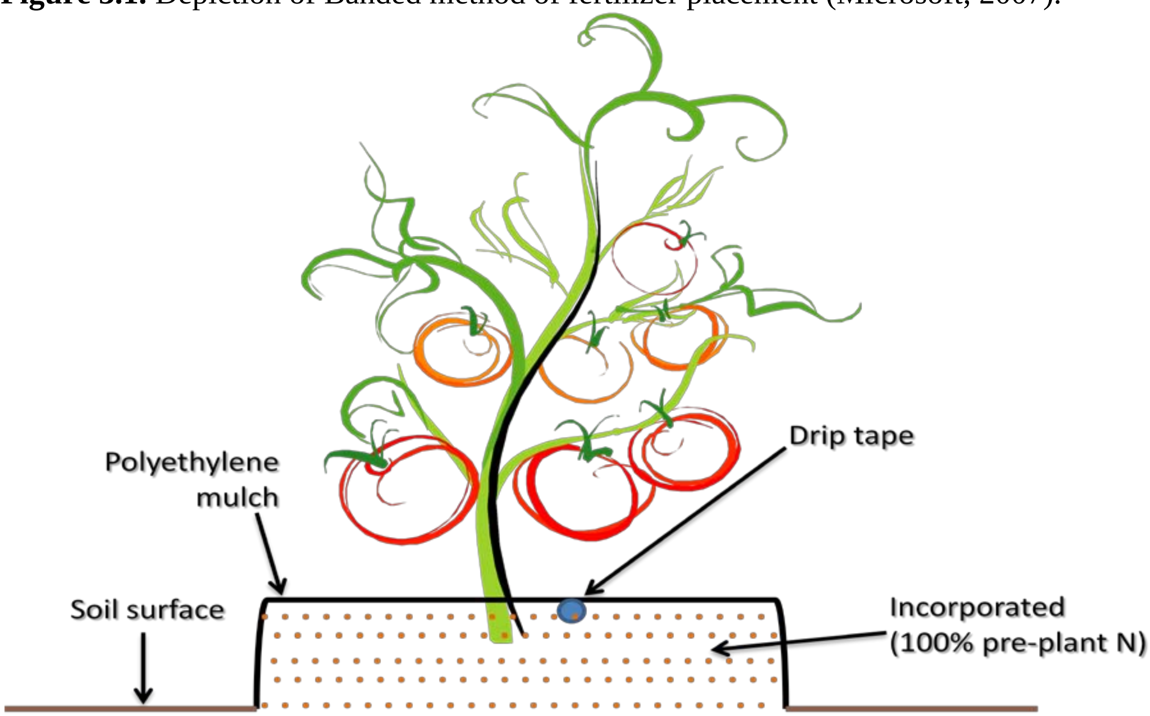

Figure 3.2. Depiction of Incorporated method of fertilizer placement (Microsoft, 2007).

4. Phosphorus Fraction Determination on a Long-Term No-Till Rotation.

4.1. Abstract

Continuous corn-wheat-soybean crop rotations on no-till land are common in the Mid-Atlantic. The objectives of this study were to determine impacts of fertilizer treatments for long-term no-till situations on pH, Mehlich-1 extractable P (M1-P) and sequentially extractable forms of P. Fertilizer treatments included 1) 0-P control, 2) P via triple superphosphate based on soil test recommendations (TSP), and N-based applications of 3) poultry litter (PL), and 4) PL amended with aluminum sulfate, or alum (PLA), which reduces ammonia concentrations in air and water soluble P in PL. Soil P fractions were determined via 1*M* NH_4Cl (loosely bound P); 0.5*M* NH_4F (aluminum bound P, Al-P); 0.1*M* NaOH (iron-bound P); 0.3*M* $Na_3C_6H_5O_7$, 1*M* $NaHCO_3$, and $Na_2S_2O_4$ (reductant soluble P); and 0.25*M* H_2SO_4 (calcium-bound P). Soil pH decreased in all treatments over time; however, trends showed PL and PLA had higher soil pH than the control and TSP treatments after 1 year. M1-P generally increased over time in PL and PLA and was greater than control and TSP treatments (157, 141, 62, and 67 mg P kg^{-1}, respectively) in 2011 due to N-based manure applications. Differences in loosely bound P were correlated to M1-P; PL and PLA generally had higher concentrations of loosely bound P than control and TSP treatments. PL and PLA were also significantly higher in Al-P than control and TSP treatments after 5 years. Additions of alum significantly reduced loosely bound P at 0-5 cm compared to PL in 2004 and 2011, but differences were not seen at depth.

4.2. Introduction

Continuous no-tillage wheat (*Triticum aestivum*), corn (*Zea mays*), and soybean (*Glycine max*) systems are commonplace in the Mid-Atlantic region. Conservation tillage practices like reduced- and no-tillage systems are best management practices that leave at least 30% of the soil surface covered by surface residues (Brady and Weil, 2004; Triplett and Dick, 2008). Conservation tillage impacts soil biological and chemical properties because of the lack of soil mixing, surface application of fertilizers and other amendments, surface mulches' effect on soil moisture and decreased soil temperature, and increased soil organic matter and surface soil acidity (Logan et al., 1991). Conservation tillage also reduced soil erosion, increased soil water availability, and increased the nutrient holding capacity of the soil according to several studies (Andraski et al., 2003; Triplett and Dick, 2008; Schomberg et al., 2009). However, without the soil mixing that occurs with conventional tillage systems, nutrient stratification of relatively immobile elements such as phosphorus (P), potassium (K), and others occur (Logan et al., 1991; Robbins and Voss, 1991; Crozier et al., 1999; Essington and Howard, 2000).

An inexpensive fertilizer source, poultry litter (PL), can supply N, P, and K, along with other micronutrients to crops in the Mid-Atlantic (Moore et al., 1995; Sims and Luka-McCafferty, 2002; Edmeades, 2003; Schomberg et al., 2009). Traditionally, PL was used as a fertilizer on crops applied to meet crop N requirements (Warren et al., 2006; White et al., 2010). However, application rates based on crop N requirements increased P concentrations in the soil surface beyond crop P requirements (Sharpley et al., 1996; Maguire et al., 2000; Sims et al., 2000). Excess soil test P can lead to agricultural runoff and nutrient leaching (Moore and Edwards, 2007). Mixing PL with alum, the common name for aluminum sulfate, is becoming a popular best management practice to mitigate environmental conditions and nutrient losses in runoff in the United States (Shreve et al., 1995; Moore and Edwards, 2005, 2007). Alum has reduced ammonia levels in poultry houses, reduced pathogens in PL, improved bird performance (due to less ammonia and fewer pathogens), reduced ventilation costs, increased N concentration in the PL, and reduced water soluble phosphorus in several studies (Moore and Edwards, 2005, 2007; Penn and Zhang, 2008).

Sharpley and coworkers (2004) found that long-term application of PL impacted the extractability and dominant forms of P in soils. The combination of excess P in the soil and P solubility is related to the amount of P loss via runoff in a rainfall event (Sharpley et al., 1996). Both fertilizers and manure add soluble P to the soil; however, over time soluble P forms can react with Al^{3+}, Fe^{3+}, and Mn^{3+} and change into insoluble, less plant available P forms such as hydroxy phosphate precipitates (Brady and Weil, 1996; Hansen et al., 2002).

Hansen et al. (2002) categorized P into three hypothetical reactivity pools in the soil: soluble P, reactive P, and stable P. The soluble pool is mainly associated with P in soil solution and contains the most plant available forms of soil P including orthophosphate anions ($H_2PO_4^-$ and HPO_4^{2-}) and some soluble organic P compounds. The amount of soluble, plant available P is less than 1% of the total P in the soil (Brady and Weil, 1996). Reactive P exists as a pool that is in equilibrium with soluble P and contains both organic and inorganic forms of P. When soluble P is lost from the system through plant uptake, leaching, or runoff, the reactive P pool replaces the lost P through desorption, dissolution, and mineralization (Hansen et al., 2002). Inorganic P in the reactive pool is associated with the soil solid phase and can be found on exchange sites and attached to relatively soluble minerals. The stable P pool is not plant available and is the largest P pool in the soil. The stable P pool is made up of organic and inorganic forms of P that are tightly bound, occluded, or insoluble. Inorganic P forms in the stable pool are mostly bound to Al, Fe, and Ca compounds and generally are not going to become available for plant uptake within one growing season (Hansen et al., 2002).

Determining inorganic P forms in a soil determines the fate of P applied as fertilizer (Chang and Jackson, 1957; Maguire et al., 2000). Phosphorus soil fractions are commonly referred to as soluble P, aluminum bound P (Al-P), iron bound P (Fe-P), reductant soluble P (RSP), and calcium bound P (Ca-P) (Maguire et al., 2000; Reiter, 2008; Zhang and Kovar, 2009). Although it was shown in several studies that PL amended with alum (PLA) can decrease the solubility of P in PLA compared with non-amended PL, there is little data on the effect of PLA on the long-term solubility and forms of P in soils (Moore et al., 1999; Sims and Luka-McCafferty, 2002; Warren et al., 2006; Moore and Edwards, 2007; Warren et al., 2008). There is also little research on the combination of effects for long-term PLA application under a no-till cropping system (O'Halloran, 1993; Sims and Luka-McCafferty, 2002; Moore and Edwards, 2007).

Soil pH impacts relative P availability and many minor elements in soil (Zn, Cu, B, Mn, Fe, and Mo, for example) (Thomas, 1996). As P remains in soil, reactions take place over time making P less soluble, and therefore, less plant available (Brady and Weil, 1996). The types of reactions that occur and the forms of P that result from the reactions are closely related to soil pH (Brady and Weil, 1996). In acidic soils, like those found in the Mid-Atlantic area, soil P reactions involve Al, Fe, and Mn ions, oxides, or hydrous oxides. Phosphorus can also adsorb on the edges of kaolinite clays and iron oxide coatings (Brady and Weil, 1996). In alkaline soils, P is most likely to fix with Ca. Phosphorus fixation occurs more rapidly at very low (<5.0) and very high (>8.0) soil pH (Brady and Weil, 1996). Therefore, as soil pH decreases, we would expect rapid P fixation to Al, Fe, and Mn in acidic soils. Likewise, as soil pH increases, we would expect rapid P fixation to Ca in alkaline soils.

Mackay and coworkers (1987) investigated stratification of soil pH after 9 years under conventional, no-till, and ridge till systems on a silty clay loam under a corn and soybean rotation in Lafayette, IN. Soil samples were taken in the row and between rows at three depths (0-75 mm, 75-275 mm, and 275-750 mm). Soil pH under no-till was lower in the top 275 mm than land that was tilled with a moldboard plow in both the row and between the rows. This pH stratification confirmed that regardless of N application (surface application or injection via anhydrous ammonia), soil pH will decrease in the topsoil in no-till systems (Mackay et al., 1987).

Reddy et al. (2009) studied the long term effects of PL versus inorganic fertilizers on conventional till, mulch till, and no-till practices on a silt loam soil. Reddy and coworkers (2009) found that conventional and mulch till plots where PL was applied long-term had significantly higher pH compared to application of inorganic fertilizer at the same rate (100 kg N ha^{-1}). Overall, PL maintained original soil pH in conventional and mulch tilled plots due to $CaCO_3$ in the PL. Application of PL at 200 kg N ha^{-1} on no-till plots resulted in the highest soil pH (6.20) and was significantly higher than no-till plots receiving 100 kg N ha^{-1} of ammonium nitrate (5.58). However, no-till plots receiving 100 kg N ha^{-1} via PL were not significantly different in soil pH than no-till plots receiving 100 kg N ha^{-1} of ammonium nitrate (5.89 and 5.58, respectively).

Sharpley et al. (1993) compared grassland soils that received PL applications for 12 to 35 years to untreated grassland soils in eastern Oklahoma. Soil pH from 0 to 5 cm averaged 6.2 and 5.6, for soils with and without PL applications, respectively. No differences in soil pH were observed below 10 cm. Similarly, Sharpley et al. (2004) examined soils from New York, Oklahoma, and Pennsylvania under various management practices. Soils receiving manure applications had significantly higher soil pH than untreated soils.

In a long-term (20 year) study, Moore and Edwards (2005) evaluated long term effects of three N sources (non-amended PL, PLA, and ammonium nitrate) on tall fescue (*Festuca arundinacea* Schreb.) on a silt loam soil. Treatments fertilized with non-amended PL had a higher pH than those fertilized with PLA. Non-amended PL had the greatest liming effect with increasing application rates. However, both PL and PLA significantly increased soil pH compared to unfertilized control plots due to large amounts of bases like $CaCO_3$. Applications of ammonium nitrate resulted in a linear decrease in soil pH as a function of application rate. Alum is meant to reduce ammonia volatilization by reducing the litter pH and pushing the ammonia/ammonium equilibrium towards non-volatile ammonium which causes PLA to have a higher N concentration. This study verified that the potential acidity from N in PLA does not exceed the base content of the litter, and therefore does not cause soil acidification problems.

When N fertilizer is applied to the soil, nitrification of ammonium takes place, releasing H^+ ions into the soil which decrease soil pH. Poultry litter contains bases such as $CaCO_3$ that help neutralize the acidity produced by nitrification and can maintain or increase soil pH (Sharpley et al., 1993; Kingery et al., 1994; Mitchell and Tu, 2006; Reddy et al., 2009). However, little research is available that demonstrates the effects of organic and inorganic fertilizer sources applied on long-term no-till soils on soil pH for coarse textured soils.

Studies have been conducted on the effects of long-term conventional tillage versus long-term no-till on plant-available P and P fractionation (Crozier et al., 1999; Essington and Howard, 2000). Crozier et al., (1999) sampled fields across North Carolina that were either conventionally tilled or no-tilled for less than 3 years, 3 to 6 years, and greater than 6 years, respectively. All fields were scheduled to be planted with corn, and sampled prior to lime and fertilizer application. For fields that were under no-till practices for at least 6 years, Mehlich-3 P extraction showed surface soils (0-10 cm) were 53 g P m^{-3} higher than underlying soils (10-20 cm). Fields sampled that were historically conventionally tilled showed surface soils (0-10 cm) were 36 g P m^{-3} higher than underlying soils (10-20 cm) (Crozier et al., 1999). Soil mixing with conventional tillage reduced stratification in the observed soils.

Essington and Howard (2000) performed a Mehlich-3 extraction and a modified Chang and Jackson (1957) sequential P extraction on disk-tilled and no-till soils fertilized with 0, 20, and 60 kg P ha^{-1} on loess-derived silt loam soil cropped in corn with a wheat cover crop. Overall, tillage did not influence Mehlich-3 P; however, Mehlich-3 P concentrations were influenced by P rate and sampling depth. Mehlich-3 P concentrations were significantly higher at shallow sample depths (0-8 cm) than at deeper depths below 8 cm (except the 0-kg ha^{-1} rate, no-till treatment), indicating vertical stratification under both tillage managements. Fertilizer P rate significantly impacted Mehlich-3 P at shallow sample depths (0-8 cm), but below 8 cm Mehlich-3 P was not influenced by any independent factor (tillage or P rate), averaging 6.9 mg kg^{-1}. Average P fractions as a percent of total P for no-till soil was 6.2% Al-P, 33.9% Fe-P, 33.9% RSP, and 4.7% Ca-P, while disk-tilled soil resulted in 5.4% Al-P, 35.6% Fe-P, 31.3% RSP, and 5.1% Ca-P. There were no significant differences between disk-tilled soil and no-till soil for all P fractions (Al-P, Fe-P, RSP, or Ca-P) in samples from 0-15cm. However, no-till soil was significantly higher in total P than disk-tilled soils from 0-15cm. A relationship between Al-P and Mehlich-3 P was found, suggesting that Al-P is wholly or fractionally plant available. Overall, tillage had little effect on the status of P in the soil, and significant differences were concentrated in the surface few centimeters. The authors predicted that more significant findings in P availability and speciation would become evident with shallower (0-4 cm) soil samples examined under different tillage treatments (Essington and Howard, 2000).

Moore and Edwards (2007) looked at the long-term effects of PL and PLA on P availability in conventionally tilled silt loam soil on a tall fescue (*Festuca arundinacea* Schreb.) cropping system. In the 7 year study, soil samples were collected and analyzed for water extractable P, Mehlich-3 P, and total P. Results showed that after 7 years, water extractable P in surface soils was greater in plots treated with PL, but Mehlich-3 P was greater in plots treated with PLA (top 5 cm). Below 5 cm, both water extractable P and Mehlich-3 P was greater using PL than PLA. Moore and Edwards hypothesized that Mehlich-3 P was greater in surface soils (top 5 cm) fertilized with PLA since P in non-amended PL would be more apt to leach because it was more soluble while the addition of alum reduced the solubility of P in PLA.

Despite the availability of literature on no-till lands and PL application, there is a lack of literature studying long-term no-till lands that received manure; specifically receiving applications of PL and PLA. Determining impacts on soil pH, soil test P, and subsequent soil P associations will benefit growers agronomically and environmentally. Additionally, monitoring changes to a 0-P control treatment will demonstrate potential P drawdown over time. The objective of this study was to determine the impacts of different inorganic and organic fertilizer regimes for long-term no-till situations by depth on (1) soil pH; (2) soil test phosphorus using the double acid (Mehlich-1) method (M1-P); and (3) sequentially extractable P fractions.

4.3. Materials and Methods

A long-term no-till two year rotation was initiated in 2003 (no-till corn monoculture from 2000-2003) in Painter, VA (37.59°N 75.77°W) on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludults) that consisted of a corn (summer) – wheat (winter) – soybean (summer) – fallow (winter) – corn (summer) rotation. Bojac sandy loam has approximately 590 g sand kg soil^{-1}, 300 g silt kg soil^{-1}, and 110 g clay kg soil^{-1} in the Ap horizon (0-45 cm). The study was fertilized via four treatments (Table 4.1) including 340 g N kg^{-1} ammonium nitrate (1, no P control), inorganic P fertilizer (2, triple super phosphate, TSP; 200 g P kg^{-1}), non-amended PL (3, PL), and PL amended with alum (4, PLA). Each plot was 41.8 m^2. In addition, each plot was duplicated directly beside itself, designated with the same respective treatment, and was named side A and side B, respectively. While side A was planted to soybeans, side B was planted to corn. Both side A and side B received fertilizer based on the designated treatment and established crop (Table 4.2). Plots received fertilizer based on the crop schedule depicted in Table 4.1. The control treatment received no P fertilizer to monitor P drawdown in the soil. Yearly P applications for TSP, PL, and PLA treatments are found in Table 4.2. The TSP treatment received inorganic P via TSP as soil tests suggested. TSP plots had sufficient concentrations of P until 2008. Therefore, from the initiation of the study in 2003 to 2008, neither the control treatment nor TSP treatment received P fertilizer. Poultry litter and PLA treatments received 6725 kg of PL prior to planting wheat and 11,210 kg of PL prior to planting corn. Actual P application rates varied by year depending on litter analysis (Table 4.2). Due to an empty faculty position, fertilizer treatments were not applied and crops were not established in 2007, however the treatment integrity remained.

Prior to planting wheat on the respective side each year, 10 soil cores were collected from each plot and depths were separated. All samples were air dried, ground to pass through a 2 mm sieve, and stored at room temperature until analyses. Tests were performed using soil samples from the three soil depths (0 to 5 cm, 5 to 15 cm, and 15 to 30 cm) in each treatment for 2004 and 2011. The analysis at depth allowed for comparison of changes through soil strata. Additionally, samples from 0 to 5 cm were analyzed from years 2000, 2008, and 2010 from side A of the study and from 2000, 2004, and 2011 from side B of the study (Table 4.2).

Soil pH

Soil pH was determined using a glass electrode connected to an Orion 5 Star pH meter (Thermo Scientific, Beverly, MA 01915), following Thomas's (1996) methodology. Ten g of air-dry soil was mixed with 10 mL of deionized water (soil:water ratio of 1:1), stirred, and allowed to stand for 10 minutes before pH was measured.

Soil Test Phosphorus

Soil test P (M1-P) was determined using the double acid (Mehlich-1) method following Virginia Tech Soil Testing Laboratory Procedures (Maguire and Heckendorn, 2011). A 1:5, soil:0.05 *M* HCl + 0.0125 *M* H_2SO_4 (5 min reaction time) was shaken and filtered through filter paper. Extracts were analyzed for P by inductively coupled plasma atomic emission spectroscopy (Spectro CircOS Vision ICP Model FVS12, Mahwah, NJ 07430).

Sequential Phosphorus Fractionation

Fractionation of inorganic P in non-calcareous soil was conducted using sequential chemical extractions (Chang and Jackson, 1957; Kuo, 1996; Maguire et al., 2000; Zhang and Kovar, 2009). Sequential extractions were carried out using 1 *M* NH_4Cl, (reaction time 30 min) for determination of loosely bound P; 0.5 *M* NH_4F, (reaction time 1 h) for determination of aluminum bound P (Al-P); 0.1 *M* NaOH, (reaction time 17 h) for determination of iron-bound P (Fe-P); 0.3 *M* $Na_3C_6H_5O_7$, 1 *M* $NaHCO_3$, and $Na_2S_2O_4$, (reaction time 15 min in 85°C water bath) for determination of reductant soluble P (RSP); and 0.25 *M* H_2SO_4, (reaction time 1 h) for determination of calcium-bound P (Ca-P). Standards were prepared using the same extracting solution as in the sample extracts. Extracts were analyzed for P by inductively coupled plasma atomic emission spectroscopy (Spectro ARCOS ICP Model FHS16, Mahwah, NJ 07430) (Kuo, 1996).

Statistics

Treatments were replicated four times and organized in a randomized complete block design. Statistical analysis was conducted using JMP 9 (2011). Significant differences between means were evaluated using Student's t comparison with a predetermined alpha value set at 0.10.

4.4. Results and Discussion

Soil pH (0-5 cm)

Soil pH from shallow soil samples (0-5 cm) was analyzed within year by treatment and within treatment by year by previously mentioned side A (Table 4.3) and side B (Table 4.4). In 2000, prior to any treatments being applied, there were no significant differences in soil pH between land areas (Table 4.3, 4.4) indicating that the field was similar amongst plots spatially, averaging 6.2. In 2008 (Table 4.3), PL and PLA soil pH were significantly higher than the control and TSP soil pH. Although not significant, the trend of higher soil pH in PL and PLA (5.12 and 5.30, respectively) versus the control and TSP treatments (5.05 and 4.91, respectively) continued in 2010. Analysis of soil pH by year within treatment showed pH did not undergo significant changes until 2010. Soil pH of all treatments in 2010 was significantly less than it was in 2000 and 2008 by 0.86 to 1.23 pH units. The decrease in pH in all treatments might have been caused by a salt effect (Kissel et al., 2009), as 2010 weather was hotter and dryer than the 30 year average (Virginia Tech, 2013).

On side B (Table 4.4), the control and TSP treatments generally follow the same trend as they did in side A when observing changes over time; in that there were no differences between 2000 and 2004 within any treatment, but pH was significantly lower in 2011. A significant increase was seen in treatments PL and PLA from 2000 to 2004. Subsequently, soil pH for PL and PLA was significantly lower in 2011 than 2000 and 2004. The increase in pH in PL and PLA in 2004 occurred after one treatment application of litter, and was possibly due to the bases ($CaCO_3$) applied via litter application. Spargo et al. (2006) found PL to have a calcium carbonate equivalence of 3.25-6.20%. However, after several years of treatment application, acidity produced by applications of inorganic N fertilizers, acids found in precipitation, and soil microbial activity overcame the liming capacity provided by $CaCO_3$ bases in the litter, and pH started to decrease. Comparing treatments within a year, in 2004, PL and PLA treatments were similar in soil pH (6.59 and 6.50, respectively) and had significantly higher pH than the control treatment (6.31) (Table 4.4). In 2011, PLA had a significantly higher pH (5.81) than PL (5.63) at 0-5 cm; however, both PL and PLA were significantly greater than the control and TSP treatments (5.40 and 5.36, respectively) (Table 4.4).

Inorganic P fertilizer, TSP, has a solution pH of 1-3 (International Plant Nutrition Institute, 2013). Poultry litter generally has a pH of approximately 8 (Maguire et al., 2008). However, additions of alum reduce PL pH and convert ammonia to ammonium. A study by Moore and Edwards (2005) report average PL and PLA pH of 8.04 and 7.59, respectively. Even though alum reduced pH, both PL and PLA contain large amounts of calcium carbonate that help resist decreases in soil pH over inorganic fertilizers (Maguire et al., 2008). Similarly, Kingery et al. (1994) demonstrated soil pH increases 0.5 pH units or more with PL applications compared to sandy loam soils under pasture receiving no PL. Target pH in Virginia for small grain – soybean double crop rotations, corn, and wheat is 6.2 (Maguire and Heckendorn, 2011). Although we observe the liming effect of PL and PLA versus TSP and no-P control treatments in 2011 (side B), soil pH for all treatments in 2010 (side A) and 2011 (side B) falls below the 6.2 target pH and warrant additional lime applications to maintain crop productivity. Soil pH plays an important role in nutrient availability to plants as low pH can bind P and cause toxicity issues from aluminum and other elements (Fox, 1979; Fox and Hoffman, 1981).

Soil pH (at depth)

Soil pH varied in a fertilizer treatment main effect, averaged over depth. In 2004, soil pH for PL, PLA, TSP, and control was 6.37, 6.26, 6.16, and 6.14, respectively ($LSD_{0.10}$ = 0.11). In 2011, soil pH for PL, PLA, TSP, and control was 6.12, 6.12, 5.92, and 5.88, respectively ($LSD_{0.10}$ = 0.11). PL and PLA had significantly higher soil pH than TSP and control treatments, which is similar to work by Maguire et al. (2008), Kingery et al. (1994), and Sharpley et al. (2004).

Analysis of soil pH by depth indicated how pH stratification occurred in no-till soils on side B of the rotation (Fig. 4.1 and 4.2). In 2004, soil pH (averaged over treatments) gradually decreased with sample depth (Fig. 4.1). Soil pH at 0-5, 5-15, and 15-30 cm was 6.43, 6.29, and 5.98, respectively ($LSD_{0.10}$ = 0.10). In 2011, soil pH (averaged over treatments) at 0-5 cm (5.55 pH) was significantly less than pH at 5-15 and 15-30 cm (6.24 and 6.23, respectively; $LSD_{0.10}$ = 0.10) (Figure 4.2). There were no significant differences between pH at depths 5-15 cm and 15-30 cm. Acidification of only the surface (0-5 cm) should be taken into consideration when liming, as smaller and/or more frequent lime applications may be used.

The lack of differences below 5 cm depth agreed with findings in Sharpley et al. (1993). Sharpley et al. (1993) observed no differences in soil pH below 10 cm between untreated (no litter or fertilizer) and treated (continuous PL applications) soils. In 2011, the increase in pH from the surface soil samples (0-5 cm) to underlying soil samples showed the impacts of stratification in no-till soils. The yearly surface application of N fertilizers, microbial activity, acid rain, et cetera, decreased the pH of the soil surface, similar to work by Fox and Hoffman (1981). However, there was no impact to soil below 5 cm. Although the soil pH of the PL and PLA treatments decreased over time (6.37 to 6.12, and 6.26 to 6.12, respectively), the pH was higher than the control and TSP treatments in 2011, agreeing with Sharpley et al. (2004) and Kingery et al. (1994), that application of PL can help offset acidifying effects of N fertilizer because of bases like $CaCO_3$ found in litter for no-tillage and pasture in the upper soil surface (Sharpley et al., 2004; Maguire et al., 2008). However, our pH results were dissimilar to Kingery et al. (1994) as their data indicated pH liming effects from litter were higher to a depth of 50 cm.

Soil Test Phosphorus (0-5 cm)

Soil test P from shallow soil samples (0-5 cm) was analyzed within year by treatment and within treatment by year by previously mentioned side A (Table 4.5) and side B (Table 4.6). In 2000, prior to any treatments being applied, there were no significant differences in M1-P between land areas (Table 4.5, 4.6) indicating the field was similar amongst the plots spatially. Additionally, all values in 2000 were above a “Very High” soil test level (55 mg P kg soil^{-1}; Mehlich 1 extract) (Maguire and Heckendorn, 2011). However, in 2004, 2008, 2010, and 2011, significant differences were present between treatments. Within year on side A, PL and PLA were significantly higher in M1-P than the control and TSP treatments in 2008 and 2010. In 2010, PLA had significantly more M1-P than all other treatments (237 mg P kg soil^{-1}). The PL treatment was significantly lower than PLA in 2010, but was significantly higher in M1-P than the control and TSP treatments. Over time on side A, no significant changes in M1-P were observed in the control and TSP treatments, while PL and PLA treatments significantly increased in M1-P from 2000 to 2010. The lack of significant differences in the control treatment indicated no significant P drawdown; while the lack of significant differences in TSP indicated adequate inorganic P application based on soil testing (Table 4.2) for side A of the rotation without over-fertilization.

Within year on side B (Table 4.6), PL and PLA were significantly higher in M1-P than the control and TSP treatments in 2004 and 2011. In 2011, PL and PLA were not significantly different (157 and 141 mg P kg soil^{-1}, respectively), but were significantly higher than the control and TSP treatments (62 and 67 mg P kg soil^{-1}, respectively). This difference in the PL and PLA treatments versus the control and TSP treatments (also seen on side A in Table 4.5) showed the potential for M1-P buildup in the soil with repeated high rates of manure applications (Table 4.2). Over time on side B, a significant decrease in M1-P was seen in the control and TSP treatments in 2011 (Table 4.6). The significant decrease in M1-P in the control treatment in 2011 is the first indication of P drawdown in the soil throughout the duration of the study. As also observed on side A, PL and PLA significantly increased in M1-P compared to concentrations found at the initiation of the study.

As expected, PL and PLA increased in M1-P over time by applying more P than crop removal rates, which is approximately 19, 16, and 26 kg P ha^{-1} for 4700, 2700, and 7500 kg grain ha^{-1} for wheat, soybean, and corn, respectively (International Plant Nutrition Institute, 2012). On side B, PL and PLA were statistically similar; however, on side A, PLA was significantly higher than PL in 2010. This was unexpected as PL and PLA analysis show similar applications of P via PL and PLA on side A of the rotation in the winter/spring of 2008/2009 and 2009/2010 (Table 4.2). Moore and Edwards (2007) saw similar results with soils fertilized with PLA having higher concentrations of Mehlich-3 extractable P than soils fertilized with PL. Moore and Edwards (2007) hypothesized PLA was higher because P in unamended litter would be more apt to leach and runoff because it is more soluble. Concentrations of M1-P for PL and PLA in 2010 and 2011 were above the 135 mg P kg soil^{-1} threshold set by Virginia DCR for the Eastern Shore and lower coastal plain of Virginia, and no further P should be applied without a P Index test (Virginia Department of Conservation and Recreation, 2005; Wolfe et al., 2005). Beck et al. (2004) stated that at a degree of P saturation (DPS) above 20%, M1-P is deemed excessive and no further fertilization is recommended for crop production. However, Beck et al. (2004) found a degree of P saturation of 20% on the Coastal Plain of Virginia correlated to a M1-P concentration of 58 mg P kg soil^{-1}; similar to the agronomic cutoff of 55 mg P kg soil^{-1} (Maguire and Heckendorn, 2011), and much lower than the concentration (135 mg P kg soil^{-1}) listed by Virginia's DCR (2005). According to Beck et al. (2004), M1-P concentrations of PL and PLA treatments in 2010 and 2011 fall between a DPS of 35% and 65% (123 and 283 mg P kg soil^{-1}, respectively). Beyond a DPS of 20%, research has shown an increased risk of P loss to the environment (Sharpley et al., 1996; Beck et al., 2004) via leaching from sandy, coarse textured soils, or runoff from agricultural fields and further P additions are not agronomically necessary (Maguire and Heckendorn, 2011).

The lack of significant difference between years in the control treatment on side A implies the soil has a high P sorption capacity and P saturation (Hansen et al., 2002). As seen in our soils, "Very High" M1-P levels can take years to reduce to levels where crops would be expected to respond to P applications. Additionally, the removal rate of P from crops is not directly equivalent to M1-P drawdown (Hansen et al., 2002). Randall et al. (1997) monitored soil test P (Bray P1) drawdown on a clay loam with a corn-soybean rotation for eight years while on another soil at 40 mg kg^{-1}, a decline of 2.9 mg kg^{-1} yr^{-1} was observed. On a soil that started at 20 mg kg^{-1}, a decline of 1.6 mg kg^{-1} yr^{-1} was observed. In our study, the control experienced a decline of 1.1 mg kg^{-1} yr^{-1} on side A and 3.0 mg kg^{-1} yr^{-1} on side B. At this rate, it will take side A 26 years and side B 3 years to reduce to M1-P concentrations (>55 mg kg^{-1}) where crops would be expected to respond to P applications. This is an economic benefit to growers, as they can forego P fertilizer applications for many years without reductions in yield.

Soil Test Phosphorus (at depth)

Analysis of Mehlich-1 extractable P by depth demonstrated how M1-P stratification occurred in no-till soils on side B of the rotation. Year was significant between 2004 (Fig. 4.3) and 2011 (Fig. 4.4) and depth×treatment interactions were observed for 2004 and 2011. In 2004 (Figure 4.3), PL and PLA at a sample depth of 0-5 cm had significantly higher M1-P than all treatments at all depths (139 and 120 mg P kg^{-1}, respectively; $LSD_{0.10}$ = 17). Concentrations of M1-P for all fertilizer treatments at 15-30 cm were statistically similar and significantly lower than all treatments at depths 0-5 and 5-15 cm. In 2011 (Figure 4.4), PL and PLA at a sample depth of 0-5 cm continued to have significantly higher M1-P than all treatments at all depths (157 and 141 mg P kg^{-1}, respectively; $LSD_{0.10}$ = 12). At sample depth 5-15 cm, PL and PLA had significantly higher M1-P (98 and 81 mg P kg^{-1}, respectively) than M1-P concentrations of TSP and control treatments at all depths. In 2011, concentrations of M1-P for all fertilizer treatments at 15-30 cm were statistically similar and significantly lower than all treatments at depths 0-5 and 5-15 cm (Figure 4.4), as was also seen in 2004 (Figure 4.3).

Soils in our study showed plots with PL and PLA applications had over 2 times more M1-P than unfertilized soil at 0-5 cm and about 1.5 times more M1-P at 5-15 cm by 2011. Kingery et al. (1994) observed on pasture lands, long-term applications of PL increased M1-P (double acid extraction) more than 6 times that of unfertilized land from 0-60 cm. Soils with PL applications from 0-15 cm and 15-30 cm resulted in approximately 225 and 70 mg P kg^{-1}, respectively; while unfertilized soils from 0-15 cm and 15-30 cm resulted in approximately 30 and 10 mg P kg^{-1}, respectively. Essington and Howard (2000) found significantly more Mehlich-3 extractable P in no-till soils (0-8 cm) fertilized with 60 kg inorganic P ha^{-1} (40.1 mg P kg^{-1}) than soils fertilized with 0 or 20 kg inorganic P ha^{-1} (6.7 and 16.2 mg P kg^{-1}, respectively). However, no significant differences were observed between fertilizer rates from 8-45 cm so no leaching was realized (Essington and Howard, 2000). Our results showed significant differences between TSP and control versus PL and PLA treatments down to 15 cm depth in 2011. The significant difference between the control and PL/PLA treatments at 5-15 cm implies possible leaching of P from the surface due to applied P exceeding plant uptake and the P sorption capacity of sandy loam soils found on the Virginia coastal plain (Kingery et al., 1994). This P leaching effect was similar to results found by Han et al. (2012) using soil cores collected from fields on the Delmarva peninsula.

Sequential Phosphorus Fractionation (0-5 cm)

Sequential fractionation data of surface soil samples (0-5 cm) from 2000, 2004, 2008, 2010, and 2011 are shown in Table 4.7. Samples from 2000, 2008, and 2010 were from previously mentioned side A of the rotation, while samples from 2000, 2004, and 2011 were from side B. Samples taken in 2000, the first year the land was no-till, and before any P fertilizer was applied, showed no significant differences in any P fraction. Total inorganic P (estimated by the sum of the P fractions) was also not significant (P = 0.4112). The lack of significant differences between treatments in 2000 indicated the land was relatively uniform in P fractions prior to the implementation of the fertilizer treatments and crop rotation. For all treatment areas in 2000, Al-P and Fe-P were the predominant P fractions in the soil, as would be expected in an acidic soil (Sims and Wolf, 1994; Brady and Weil, 1996) (Table 4.3, Table 4.4). Generally, the smallest soil P fraction was loosely bound P.

In 2004, loosely bound P was significantly different between fertilizer treatments while no other fraction differed (Table 4.7). The PL treatment contained the greatest concentration of loosely bound P (22.7 mg P kg soil^{-1}), while the control treatment contained the lowest concentration (6.5 mg P kg soil^{-1}). After one fertilizer application (Table 4.2), Al-P and Fe-P were still the predominant P fractions in the soil in all treatments.

Surface soil samples (0-5 cm) in 2008 demonstrated that PL and PLA treatments contained significantly more loosely bound P than the control and TSP treatments (Table 4.7). Significantly more loosely bound P in PL and PLA treatments is indicative of high rate manure applications. Treatments PL and PLA also contained significantly more Al-P than the control and TSP treatments. PL and PLA treatments in 2008 had significantly higher soil pH than the control and TSP treatments, yet PL and PLA contained greater concentrations of Al-P than the control and TSP treatments due to overall higher P applications. This data mirrors P associations found by Yuan et al. (1960) on sandy loam soils where fertilizer P additions were primarily associated with Al. Yuan et al. (1960) observed Al-P associations that linearly increased as P fertilizer was applied; Al-P represented 68% of total extractable P with a concentration of 358 mg P kg^{-1}. Concentrations of Al-P for PL and PLA treatments in 2008 were 313 and 340 mg P kg^{-1}, resulting in 45% and 46%, respectively of total inorganic P. Litter analysis indicated Al concentrations of approximately 513 and 8430 mg Al kg^{-1} for PL and PLA, respectively. Applied at rates indicated in Table 4.1, PL and PLA apply approximately 9 and 151 kg Al ha^{-1}, respectively over a 2 year (1 full crop rotation) time period, which is small compared to overall

Al found in soil. Therefore, additional P associations with Al were based on our overall acidic soil environment and not due to additional Al added to the soil with the PL amendment.

In 2010, there were significant differences between treatments in concentrations of loosely bound P, Al-P, RSP, Ca-P, and total inorganic P (Table 4.7). PLA had the highest concentrations of Al-P, RSP, Ca-P fractions and total inorganic P. PLA and PL continued to be significantly higher in loosely bound P than the control and TSP treatments (Table 4.7) due to repeated high rate manure applications (Table 4.2) which mirrored Mehlich 1-extractable M1-P (Table 4.5). No significant differences between treatments were found in soil pH in 2010 (Table 4.3); however, PL and PLA had significantly more Al-P (348 and 447 mg P kg $soil^{-1}$, respectively) than the control and TSP treatments (237 and 230 mg P kg $soil^{-1}$, respectively) with 10% more P being associated with Al in manured treatments, similar to Yuan et al. (1960). Sharpley et al. (2004) found in heavily manured soils, P became more likely to be precipitated as Ca-P. This was not evident in PL and PLA in our study, as all treatments had 5 to 6% of inorganic P extracted as Ca-P. In 2010, Al-P and Fe-P continued to be dominant P fractions in all treatments.

In 2011, there were significant differences between treatments in loosely bound P, Al-P, and total inorganic P in shallow soil samples (Table 4.7). PL and PLA had significantly more loosely bound P than the control and TSP treatments; however, PL had significantly more loosely bound P than PLA. Statistical separation of the concentration of loosely bound P in PL and PLA is likely due to alum reducing the solubility of P in PLA. Shreve et al. (1995) and Moore et al. (1999) both found significant P reductions in runoff on fields fertilized with PLA versus non-amended PL; however, these studies did not investigate P fractions in the soil. Moore and Edwards (2007) found significantly more water soluble P in soils treated with non-amended

PL versus PLA. However, Mehlich III-extractable P was greater in surface soils fertilized with PLA versus non-amended PL. The relationship between water soluble P and Mehlich III P resulted in a greater slope for soils fertilized with non-amended PL. A greater slope indicated that for a given Mehlich III P concentration, there was more water and acid soluble P in soils that received non-amended PL compared to PLA (Moore and Edwards, 2007). No significant differences in M1-P concentrations (via Mehlich I) were observed between PL and PLA in 2011 (Table 4.6). However, the higher concentration of loosely bound P in PL in 2011 (Table 4.7) coincides with the greater water soluble P findings in Moore and Edwards (2007). Treatments PL and PLA were also significantly higher in Al-P than the control and TSP treatments, and is likely due to higher P additions and not preferential partitioning of P by Al additives.

In surface soil samples (0-5 cm), loosely bound P and Ca-P generally represented the smallest fraction of soil P. Aluminum bound P and Fe-P fractions contained the greatest concentrations of soil P for all treatments and years. When combined, Al-P and Fe-P fractions contained the majority (>70%) of inorganic soil P. This agrees with several other authors who found the majority of P interactions were with Al and Fe in acidic soils (Yuan et al., 1960; Pierzynski et al., 1990; Sims and Wolf, 1994; Mozaffari and Sims, 1996; Maguire et al., 2000). Reductant soluble P and Ca-P were generally not impacted by fertilizer treatment over the period of the study on no-till soils and accounted for approximately 10% and 7% of total inorganic soil P, respectively. Total inorganic P was significantly impacted by fertilizer treatments starting in 2010, 7 years after the initiation of the study. Significant differences in total inorganic P continued to occur in 2011. Further applications of PL, as defined in treatments PL and PLA (Table 4.1) will likely continue to increase total inorganic soil P when applied above crop removal rates and will further increase Al-P associations in our climate and soils, regardless of litter amendments.

Sequential Phosphorus Fractionation (at depth)

Sequential soil P fractions by depth for 2011 were depicted in Fig. 4.5, 4.6, 4.7, 4.8, 4.9, and 4.10 for loosely bound P, Al-P, Fe-P, RSP, Ca-P, and total inorganic P, respectively. Loosely bound P, Al-P, Ca-P, and total inorganic P had significant treatment×depth interactions. Iron bound P and RSP fractions were significant only by depth and are averaged across treatments.

Significant differences in loosely bound P (Figure 4.5) generally mirror differences found in 2011 M1-P (Figure 4.4). Concentrations of loosely bound P was the greatest in PL at 0-5 cm (18.1 mg P kg^{-1}) followed by PLA at 0-5 cm (13.0 mg P kg^{-1}), as also seen in Table 4.7. The increase in loosely bound P in PL versus PLA might be due to alum reducing the solubility of P in the PLA (Moore and Edwards, 2007). Loosely bound P was significantly higher in PL at 5-15 cm (6.3 mg P kg^{-1}) than TSP (2.7 mg P kg^{-1}), indicating the soils receiving PL were possibly leaching P from the surface due to applied P exceeding plant uptake and the P sorption capacity (Kingery et al., 1994). Similar to 2011 M1-P (Figure 4.4), concentrations of loosely bound P were not significantly different between any fertilizer treatments at 15-30 cm (Figure 4.5).

The highest concentrations of Al-P (Figure 4.6) were found in PL and PLA at 0-5 cm (310 and 322 mg P kg^{-1}, respectively; $LSD_{0.10} = 47$) as also seen in Table 4.7. As discussed earlier, we attribute the increase in Al-P to our native acidic soil environment. Concentrations of Al-P in all treatments at 15-30 cm were statistically similar and statistically lower than all other data points at 0-5 and 5-15 cm.

Iron bound P was only significant by depth in 2011 (Figure 4.7). Concentrations of 270, 201, and 155 mg P kg^{-1} at 0-5, 5-15, and 15-30 cm, respectively, were all significantly different

($LSD_{0.10}$ = 25). Reductant soluble P was also significant by depth in 2011 (Figure 4.8). Concentrations at 0-5 and 15-30 cm (67 and 67 mg P kg^{-1}, respectively) were statistically different from the concentration at 5-15 cm (78 mg P kg^{-1}). Calcium-bound P (Figure 4.9) showed few meaningful significant differences in 2011 ($LSD_{0.10}$ = 7). Overall, P associations showed no strong correlation with any of these fractions, as found by others (Yuan et al., 1960; Essington and Howard, 2000). Total inorganic P mirrored M1-P, loosely bound P, and Al-P with PL and PLA at 0-5 cm (710 and 729 mg P kg^{-1}, respectively) significantly higher ($LSD_{0.10}$ = 105) than all other data (Figure 4.10) and showed little difference below 5 cm depths.

4.5. Conclusions

Soil pH generally decreased over time due to acidification via N fertilizers and other environmental pressures such as acid rain and microbial activity; however, PL and PLA added bases to resist this acidification. Averaged over treatments, soil pH at depth was lower only in the soil surface (0-5 cm), and should be taken into consideration when liming, as smaller and/or more frequent lime applications may be used. Soil test P was significantly higher in PL and PLA compared to control and TSP treatments in every year due to N-based manure applications where P rates above crop removal were applied, which increased M1-P over time. High M1-P concentrations found in PL and PLA treatments can cause environmental problems via runoff and leaching from coarse textured soils. Concentrations of M1-P at depth indicated P leaching in the PL and PLA treatments, as PL and PLA contained greater concentrations of M1-P than the control and TSP treatments at 5-15 cm depth. Concentrations of M1-P in the 0-P control treatment did not fall below the agronomic cutoff of 55 mg P kg^{-1} during the study, suggesting soils testing “Very High” in soil test P in the Mid-Atlantic region, may take over 10 years before

P fertilizer is needed. Overall, loosely bound P and Al-P fractions varied the greatest in 0-5 cm soil samples with fertilizer P additions. As expected, PL and PLA treatments contained greater concentrations of loosely bound P and Al-P than the control and TSP treatments, due to greater P additions. Additions of alum, compared to non-amended PL, reduced loosely bound P in 0-5 cm soil samples, possibly reducing P concentrations in runoff. However, PLA did not generally increase Al-P associations when compared to non-amended PL, implying P applications above crop removal rates will increase concentrations of Al-P, regardless of litter amendment, in this long-term corn-wheat-soybean no-tillage system in the Mid-Atlantic region.

4.6. Acknowledgements

We would like to thank the funders of this project, The Maryland Grain Producers Utilization Board, for helping to make this research possible. We would also like to thank the staff at the Virginia Tech Eastern Shore AREC in Painter, Virginia, for their help, hard work, and dedication to this project.

4.7. References

Andraski, T.W., L.G. Bundy, and K.C. Kilian. 2003. Manure history and long-term tillage effects on soil properties and phosphorus losses in runoff. J. Environ. Qual. 32:1782-1789.

Beck, M.A., L.W. Zelazny, W.L. Daniels, and G.L. Mullins. 2004. Using the Mehlich-1 extract to estimate soil phosphorus saturation for environmental risk assessment. Soil Sci. Soc. Am. J. 68:1762-1771.

Brady, N.C., and R.R. Weil. 1996. Soil phosphorus and potassium In: A. Kupchik, editor, The nature and properties of soils. Prentice-Hall, Inc., Upper Sadle River, NJ. p. 445-487.

Brady, N.C., and R.R. Weil. 2004. Elements of the nature and properties of soils. Pearson Education, Inc., Upper Saddle River, NJ.

Chang, S.C., and M.L. Jackson. 1957. Fractionation of soil phosphorus. Soil Sci. 84:133-144.

Commonwealth of Virginia. 2005. Virginia nutrient management standards and criteria. Virginia Dep. of Conserv. and Recreation. http://www.dcr.virginia.gov/documents/StandardsandCriteria.pdf (accessed 18 March 2011).

Crozier, C.R., G.C. Naderman, M.R. Tucker, and R.E. Sugg. 1999. Nutrient and pH stratification with conventional and no-till management. Commun. Soil Sci. Plant Anal. 30:65-74.

Edmeades, D.C. 2003. The long-term effects of manures and fertilisers on soil productivity and quality: A review. Nutr. Cycl. Agroecosyst. 66:165-180.

Essington, M.E., and D.D. Howard. 2000. Phosphorus availability and speciation in long-term no-till and disk-till soil. Soil Sci. 165:144-152.

Fox, R.H. 1979. Soil pH, aluminum saturation, and corn grain yield. Soil Sci. 127:330-334.

Fox, R.H., and L.D. Hoffman. 1981. The effect of N fertilizer source on grain yield, N uptake, soil pH, and lime requirement in no-till corn. Agron. J. 73:891-895.

Han, K., P. Kleinman, R. Bryant, M.S. Reiter, J. McGrath, C. Church, et al. 2012. Effect of tillage on phosphorus leaching through coastal plain soils, ASA, CSSA, and SSSA, ASA, CSSA, and SSSA International Annual Meeting.

Hansen, N.C., T.C. Daniel, A.N. Sharpley, and J.L. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. J. Soil Water Conserv. 57:408-417.

International Plant Nutrition Institute. 2012. Ipni estimates of nutrient uptake and removal. IPNI. http://www.ipni.net/article/IPNI-3296 (accessed Feb. 15 2013).

International Plant Nutrition Institute. 2013. Triple superphosphate. Nutrient Source Specifics. International Plant Nutrition Institute. http://www.ipni.net/publication/nss.nsf/0/35039C5F78D8740C852579AF0076567A/$FILE/NSS-14%20Triple%20Superphosphate.pdf (accessed 12 Feb. 2013).

JMP 9. 2011. SAS Institute Inc., Cary, NC.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23:139-147.

Kissel, D.E., L. Sonon, P.F. Vendrell, and R.A. Isaac. 2009. Salt concentration and measurement of soil pH. Commun. Soil Sci. Plant Anal. 40:179-187.

Kuo, S. 1996. Phosphorus. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. SSSA and ASA, Madison, WI. p. 869-919.

Large, E.C. 1954. Growth stages in cereals illustration of the feekes scale. Plant Pathology 3:128-129.

Logan, T.J., R. Lal, and W.A. Dick. 1991. Tillage systems and soil properties in north-america. Soil Tillage Res. 20:241-270.

Mackay, A.D., E.J. Kladivko, S.A. Barber, and D.R. Griffith. 1987. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci. Soc. Am. J. 51:970-974.

Maguire, R.O., and S.E. Heckendorn. 2011. Soil test recommendations for Virginia. Virginia Cooperative Extension. http://www.soiltest.vt.edu/PDF/recommendation-guidebook.pdf (accessed 1 Feb 2013).

Maguire, R.O., G.L. Mullins, and M. Brosius. 2008. Evaluating long-term nitrogen- versus phosphorus-based nutrient management of poultry litter. J. Environ. Qual. 37:1810-1816.

Maguire, R.O., J.T. Sims, and F.J. Coale. 2000. Phosphorus fractionation in biosolids-amended soils: Relationship to soluble and desorbable phosphorus. Soil Sci. Soc. Am. J. 64:2018-2024.

Mitchell, C.C., and S.X. Tu. 2006. Nutrient accumulation and movement from poultry litter. Soil Sci. Soc. Am. J. 70:2146-2153.

Moore, P.A., T.C. Daniel, and D.R. Edwards. 1999. Reducing phosphorus runoff and improving poultry production with alum. Poult. Sci. 78:692-698.

Moore, P.A., T.C. Daniel, A.N. Sharpley, and C.W. Wood. 1995. Poultry manure management - environmentally sound options. J. Soil Water Conserv. 50:321-327.

Moore, P.A., and D.R. Edwards. 2005. Long-term effects of poultry litter, alum-treated litter, and ammonium nitrate on aluminum availability soils. J. Environ. Qual. 34:2104-2111.

Moore, P.A., and D.R. Edwards. 2007. Long-term effects of poultry litter, alum-treated litter, and ammonium nitrate on phosphorus availability in soils. J. Environ. Qual. 36:163-174.

Mozaffari, M., and J.T. Sims. 1996. Phosphorus transformations in poultry litter-amended soils of the Atlantic coastal plain. J. Environ. Qual. 25:1357-1365.

O'Halloran, I.P. 1993. Effect of tillage and fertilization on inorganic and organic soil-phosphorus. Can. J. Soil Sci. 73:359-369.

Penn, C., and H. Zhang. 2008. Alum-treated poultry litter as a fertilizer source, Publ. PSS-2254, Oklahoma Cooperative Extension Service, Oklahoma State University.

Pierzynski, G.M., T.J. Logan, S.J. Traina, and J.M. Bigham. 1990. Phosphorus chemistry and mineralogy in excessively fertilized soils - quantitative-analysis of phosphorus-rich particles. Soil Sci. Soc. Am. J. 54:1576-1583.

Randall, G.W., T.K. Iragavarapu, and S.D. Evans. 1997. Long-term P and K applications: I. Effect on soil test incline and decline rates and critical soil test levels. J. Prod. Agric. 10:565-571.

Reddy, S.S., E.Z. Nyakatawa, K.C. Reddy, R.L. Raper, D.W. Reeves, and J.L. Lemunyon. 2009. Long-term effects of poultry litter and conservation tillage on crop yields and soil phosphorus in cotton-cotton-corn rotation. Field Crop. Res. 114:311-319.

Reiter, M.S. 2008. Environmental and agronomic evaluation of value-added nitrogen fortified poultry litter and biosolids fertilizers. Ph.D. diss., Univ. of Arkansas, Fayetteville.

Robbins, S.G., and R.D. Voss. 1991. Phosphorus and potassium stratification in conservation tillage systems. J. Soil Water Conserv. 46:298-300.

Schomberg, H.H., D.M. Endale, M.B. Jenkins, R.R. Sharpe, D.S. Fisher, M.L. Cabrera, et al. 2009. Soil test nutrient changes induced by poultry litter under conventional tillage and no-tillage. Soil Sci. Soc. Am. J. 73:154-163.

Sharpley, A., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil Water Conserv. 51:160-166.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2004. Amounts, forms, and solubility of phosphorus in soils receiving manure. Soil Sci. Soc. Am. J. 68:2048-2057.

Sharpley, A.N., S.J. Smith, and W.R. Bain. 1993. Nitrogen and phosphorus fate from long-term poultry litter applications to Oklahoma soils. Soil Sci. Soc. Am. J. 57:1131-1137.

Shreve, B.R., P.A. Moore, T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Reduction of phosphorus in runoff from field-applied poultry litter using chemical amendments. J. Environ. Qual. 24:106-111.

Sims, J.T., A.C. Edwards, O.F. Schoumans, and R.R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agricultural management practices. J. Environ. Qual. 29:60-71.

Sims, J.T., and N.J. Luka-McCafferty. 2002. On-farm evaluation of aluminum sulfate (alum) as a poultry litter amendment: Effects on litter properties. J. Environ. Qual. 31:2066-2073.

Sims, J.T., and D.C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. In: D.L. Sparks, editor, Advances in agronomy. Academic Press, Inc., San Diego, CA. p. 1-83.

Spargo, J.T., G.K. Evanylo, and M.M. Alley. 2006. Repeated compost application effects on phosphorus runoff in the Virginia piedmont. J. Environ. Qual. 35:2342-2351.

Thomas, G.W. 1996. Soil pH and soil acidity. In: D.L. Sparks, editor, Methods of soil analysis, part 3 - chemical methods. SSSA and ASA, Madison. p. 475-490.

Triplett, G.B., and W.A. Dick. 2008. No-tillage crop production: A revolution in agriculture! Agron. J. 100:S153-S165.

Virginia Department of Conservation and Recreation. 2005. Virginia nutrient management standards and criteria, Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation, Richmond, VA.

Virginia Tech. 2013. Eastern shore agricultural research and extension center weather data. Virginia Tech. http://www.arec.vaes.vt.edu/eastern-shore/weather/weather-data.html (accessed 1 March 2013).

Warren, J.G., C.J. Penn, J.M. McGrath, and K. Sistani. 2008. The impact of alum addition on organic P transformations in poultry litter and litter-amended soil. J. Environ. Qual. 37:469-476.

Warren, J.G., S.B. Phillips, G.L. Mullins, and L.W. Zelazny. 2006. Impact of alum-treated poultry litter applications on fescue production and soil phosphorus fractions. Soil Sci. Soc. Am. J. 70:1957-1966.

White, J.W., F.J. Coale, J.T. Sims, and A.L. Shober. 2010. Phosphorus runoff from waste water treatment biosolids and poultry litter applied to agricultural soils. J. Environ. Qual. 39:314-323.

Wolfe, M.L., J. Pease, L. Zelazny, L. Daniels, and G. Mullins. 2005. Virginia phosphorus index version 2.0, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Yuan, T.L., W.K. Robertson, and J.R. Neller. 1960. Forms of newly fixed phosphorus in three acid sandy soils. Soil Science Society Proceedings 24:447-450.

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415-421.

Zhang, H., and J.L. Kovar. 2009. Fractionation of soil phosphorus. In: J.L. Kovar , and G.M. Pierzynski, editor, Methods of phosphorus analysis for soils, sediments, residuals, and waters. Virginia Tech.

Table 4.1. Nitrogen (N) and phosphorus (P) treatment schedule for a continuous no-tillage corn-wheat-soybean rotation fertilized with triple super phosphate (TSP), poultry litter (PL), and PL amended with alum (PLA) treatments on a Bojac sandy loam on the Delmarva peninsula.

Treatment	Source	PP§ Wheat	Winter	GS25† Wheat	GS30‡ Wheat	Soybeans	Winter	PP Corn	V6¶ Corn
1 (Control)	IF††	34 kg N	-	N as needed	N as needed IF	-	-	56 kg N starter	140 kg N
2 (TSP)	IF	34 kg N; P as needed	-	N as needed	N as needed IF	-	-	56 kg N starter	140 kg N
3 (PL)	PL + IF	34 kg N IF	6725 kg PL	-	N as needed IF	-	11,210 kg PL	56 kg N starter IF	140 kg N IF
4 (PLA)	Alum PL + IF	34 kg N IF	6725 kg PLA	-	N as needed IF	-	11,210 kg PLA	56 kg N starter IF	140 kg N IF

† Zadoks' wheat growth stage 25 (~ mid-tillering) (Zadoks et al., 1974).
‡ Zadoks' wheat growth stage 30 (~leaf sheaths strongly erected; tillering ending) (Zadoks et al., 1974).
§ Pre-plant.
¶ Vegetative growth stage 6; where the leaf collar of the 6th leaf just becomes visible (Large, 1954).
# Standard.
†† Inorganic fertilizer (ammonium nitrate; 340 g N kg^{-1}).

Table 4.2. Phosphorus (P) applications for a continuous no-tillage corn-wheat-soybean rotation fertilized treatments on a Bojac sandy loam on the Delmarva peninsula.

		Side A				Side B			
Season	Year	Crop	TSP†	PL‡	PLA§	Crop	TSP	PL	PLA
			-------kg P ha^{-1}-------				------kg P ha^{-1}------		
Winter/Spring	2003/2004	Wheat	0	74	72	Fallow	0	123	120
Summer	2004	Soybean	0	0	0	Corn	0	0	0
Winter/Spring	2004/2005	Fallow	0	145	139	Wheat	0	86	92
Summer	2005	Corn	0	0	0	Soybean	0	0	0
Winter/Spring	2005/2006	Wheat	0	59	70	Fallow	0	99	117
Summer	2006	Soybean	0	0	0	Corn	0	0	0
Winter/Spring	2006/2007	Fallow	0	143	165	Wheat	0	62	68
Summer	2007	Fallow	0	0	0	Fallow	0	0	0
Winter/Spring	2007/2008	Fallow	0	0	0	Fallow	0	0	0
Summer	2008	Fallow	0	0	0	Fallow	0	0	0
Winter/Spring	2008/2009	Wheat	20	66	60	Fallow	0	102	97
Summer	2009	Soybean	0	0	0	Corn	0	0	0
Winter/Spring	2009/2010	Fallow	0	111	105	Wheat	10	120	183
Summer	2010	Corn	0	0	0	Soybean	0	0	0
Winter/Spring	2010/2011	Wheat	10	67	63	Fallow	0	125	100
Summer	2011	Soybean	0	0	0	Corn	0	0	0
Total			30	665	674		10	717	777

†Triple superphosphate (TSP) treatment.
‡Poultry litter (PL) treatment.
§Poultry litter amended with alum (PLA) treatment.

Table 4.3. Soil pH (0-5 cm) from four fertilizer regimes in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula (side A of rotation).

Treatment		2000	2008	2010
#		---------------------------	pH	---------------------------
1†	Control	6.21 a‡ A§	6.01 b A	5.05 a B
2	TSP	6.08 a A	6.02 b A	4.91 a B
3	PL	6.35 a A	6.31 a A	5.12 a B
4	PLA	6.16 a A	6.39 a A	5.30 a B

†Treatment regimes found in Table 4.1.
‡Means followed by different lower case letters within a column are significantly different (*alpha* = 0.10).
§Means followed by different upper case letters within a row are significantly different (*alpha* = 0.10).
¶Not significant.

Table 4.4. Soil pH (0-5 cm) from four fertilizer regimes in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula (side B of rotation).

Treatment		2000	2004	2011
#		---------------------------	pH	---------------------------
1†	Control	6.21 a‡ A§	6.31 c A	5.40 c B
2	TSP	6.08 a A	6.33 bc A	5.36 c B
3	PL	6.35 a B	6.59 a A	5.63 b C
4	PLA	6.16 a B	6.50 ab A	5.81 a C

†Treatment regimes found in Table 4.1.
‡Means followed by different lower case letters within a column are significantly different (*alpha* = 0.10).
§Means followed by different upper case letters within a row are significantly different (*alpha* = 0.10).
¶Not significant.

Table 4.5. Soil test P (0-5 cm) from four fertilizer regimes in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula (side A of rotation).

Treatment		2000	2008	2010
#		---------------------mg P kg soil^{-1}---------------------		
1†	Control	95 a‡ A§	89 b A	84 c A
2	TSP	96 a A	96 b A	102 c A
3	PL	101 a B	170 a A	187 b A
4	PLA	88 a C	172 a B	237 a A

†Treatment regimes found in Table 4.1.

‡Means followed by different lower case letters within a column are significantly different (*alpha* = 0.10).

§Means followed by different upper case letters within a row are significantly different (*alpha* = 0.10).

¶Not significant.

Table 4.6. Soil test P (0-5 cm) from four fertilizer regimes in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula (side B of rotation).

Treatment		2000	2004	2011
#		---------------------mg P kg soil^{-1}---------------------		
1†	Control	95 a‡ A§	89 b§ A	62 b B
2	TSP	96 a A	92 b A	67 b B
3	PL	101 a B	139 a A	157 a A
4	PLA	88 a B	120 a AB	141 a A

†Treatment regimes found in Table 4.1.

‡Means followed by different lower case letters within a column are significantly different (*alpha* = 0.10).

§Means followed by different upper case letters within a row are significantly different (*alpha* = 0.10).

¶Not significant.

Table 4.7. Sequential P fractionation from soil samples (0-5 cm) from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

Treatment		Loosely bound P	Al-P	Fe-P	RSP†	Ca-P	$LSD_{0.10}$	Total‡
				2000				
			----------mg P kg soil^{-1}----------					
1§	Control	8.4 C¶	187 A	218 A	62 B	38 BC	45.6	513
2	TSP	7.1 C	186 A	193 A	61 B	35 B	37.5	482
3	PL	9.9 E	147 B	171 A	53 C	39 D	12.1	420
4	PLA	6.4 C	148 A	167 A	49 B	37 B	20.9	407
$LSD_{0.10}$		NS	NS	NS	NS	NS		NS
				2004				
1	Control	6.5 c†† D	192 B	234 A	60 C	46 C	34.5	539
2	TSP	7.4 bc C	171 A	201 A	61 B	40 BC	44.7	481
3	PL	22.7 a D	196 A	189 A	63 B	46 C	12.6	516
4	PLA	12.3 b C	211 A	195 A	59 B	37 BC	30.4	514
$LSD_{0.10}$		5.5	NS	NS	NS	NS		NS
				2008				
1	Control	8.1 b D	227 b B	289 A	55 C	54 C	39.6	633
2	TSP	8.9 b B	208 b A	249 A	50 B	38 B	50.9	555
3	PL	24.7 a D	313 a A	252 B	58 C	51 CD	28.0	699
4	PLA	21.9 a D	340 a A	263 B	62 C	47 CD	25.4	734
$LSD_{0.10}$		5.2	58	NS	NS	NS		NS
				2010				
1	Control	8.5 b D	237 c B	288 A	52 b C	32 c CD	34.4	618 bc
2	TSP	12.0 b B	230 c A	245 A	50 b B	34 bc B	43.3	570 c
3	PL	33.3 a D	348 b A	243 B	53 b C	41 b CD	16.9	719 b
4	PLA	38.6 a C	447 a A	252 B	64 a C	57 a C	35.5	859 a
$LSD_{0.10}$		6.3	72	NS	8	9		135
				2011				
1	Control	4.7 c D	199 b B	272 A	65 C	29 D	27.2	569 b
2	TSP	5.2 c D	183 b B	245 A	63 C	29 CD	43.6	525 b
3	PL	18.1 a C	310 a A	287 A	60 B	35 BC	25.6	710 a
4	PLA	13.0 b D	322 a A	278 B	79 C	38 D	33.0	729 a
$LSD_{0.10}$		4.6	51	NS	NS	NS		119

†Reductant soluble P.
‡Sum of all sequentially extractable forms.
§Treatment regimes found in Table 4.1.
¶ Means followed by different upper case letters within a row are significantly different (*alpha* = 0.10).
†† Means followed by different lower case letters within a column within a specific year are significantly different (*alpha* = 0.10).

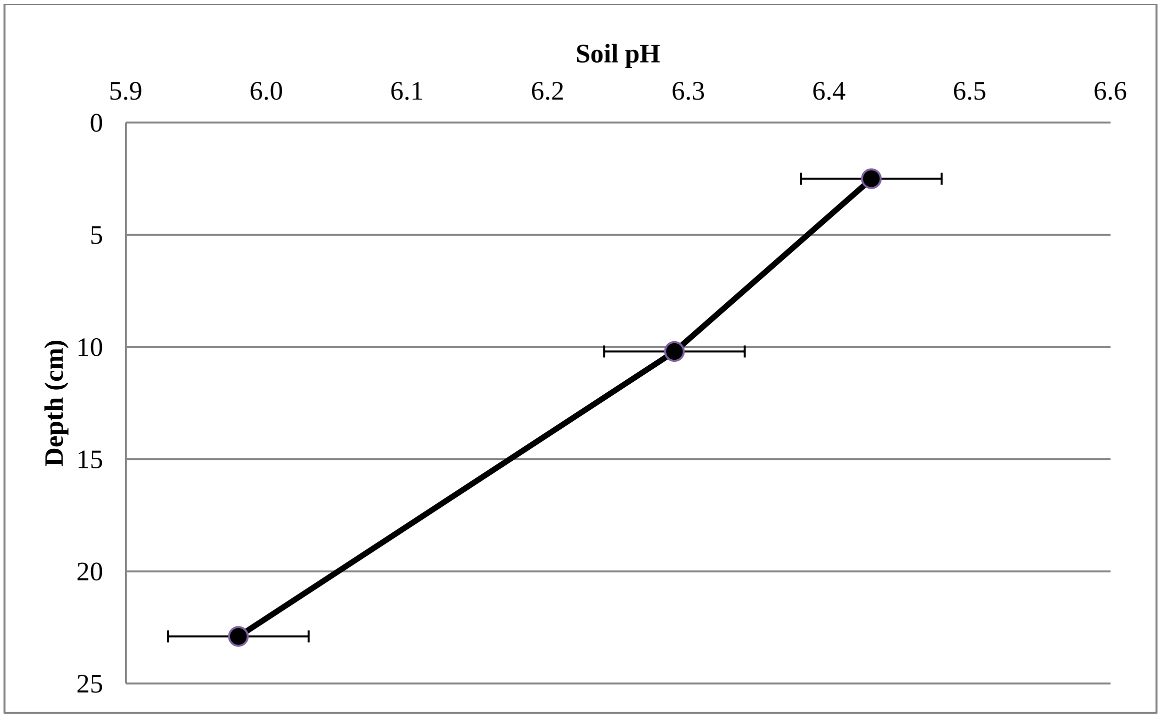

Figure 4.1. Soil pH in 2004 ($LSD_{0.10}$ = 0.10) by depth in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula (averaged over treatments).

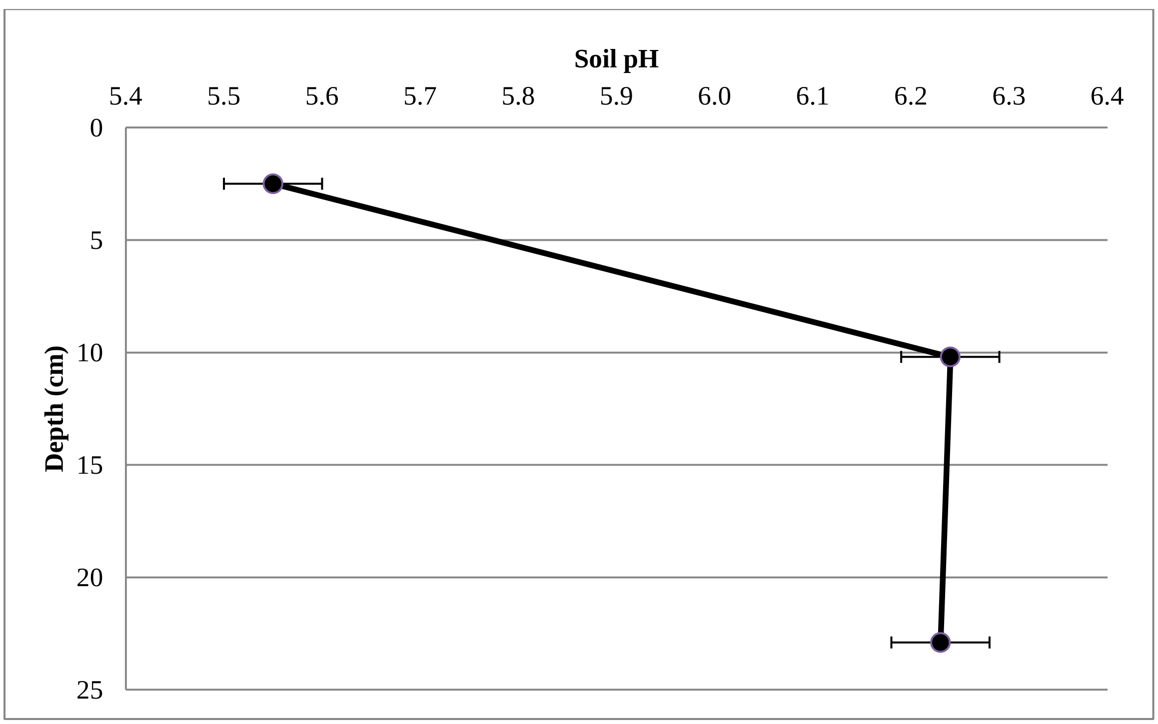

Figure 4.2. Soil pH in 2011 ($LSD_{0.10}$ = 0.10) by depth in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula (averaged over treatments).

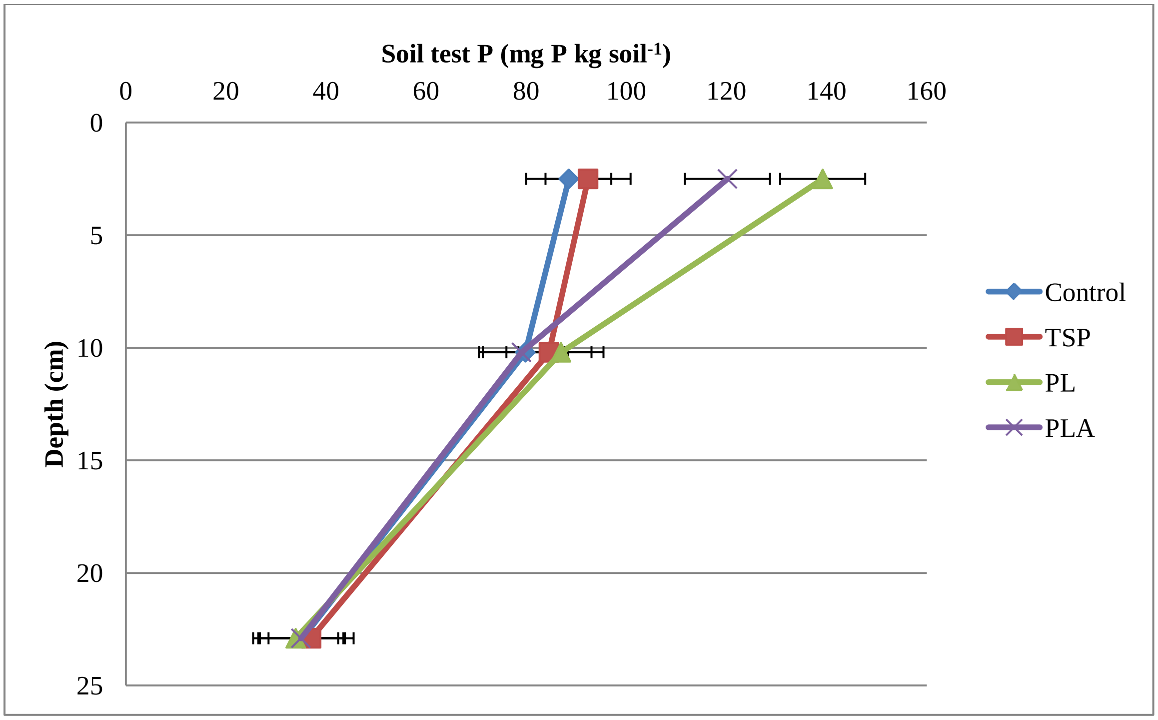

Figure 4.3. Soil test P (Mehlich-1 extractable P) in 2004 ($LSD_{0.10}$ = 17) by depth from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

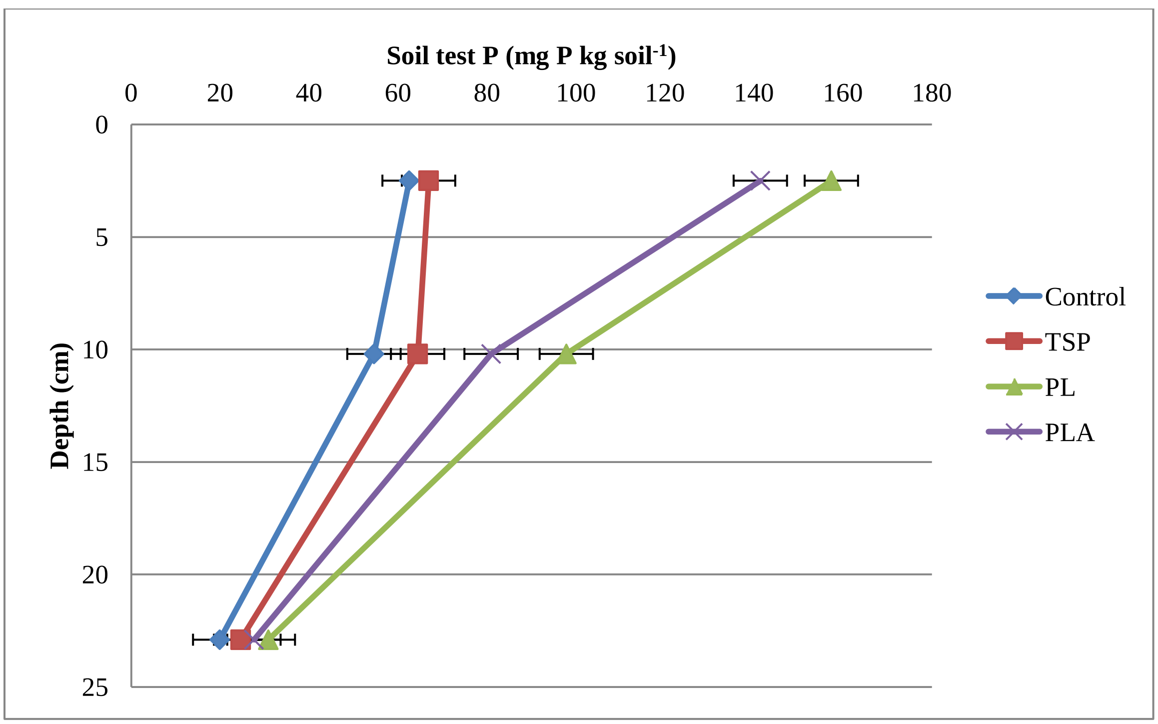

Figure 4.4. Soil test P (Mehlich-1 extractable P) in 2011 ($LSD_{0.10}$ = 12) by depth from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

Figure 4.5. Loosely bound P concentrations extracted via sequential fractionation on soil samples taken at depth (0-5, 5-15, 15-30 cm) in 2011 ($LSD_{0.10}$ = 3.0) from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

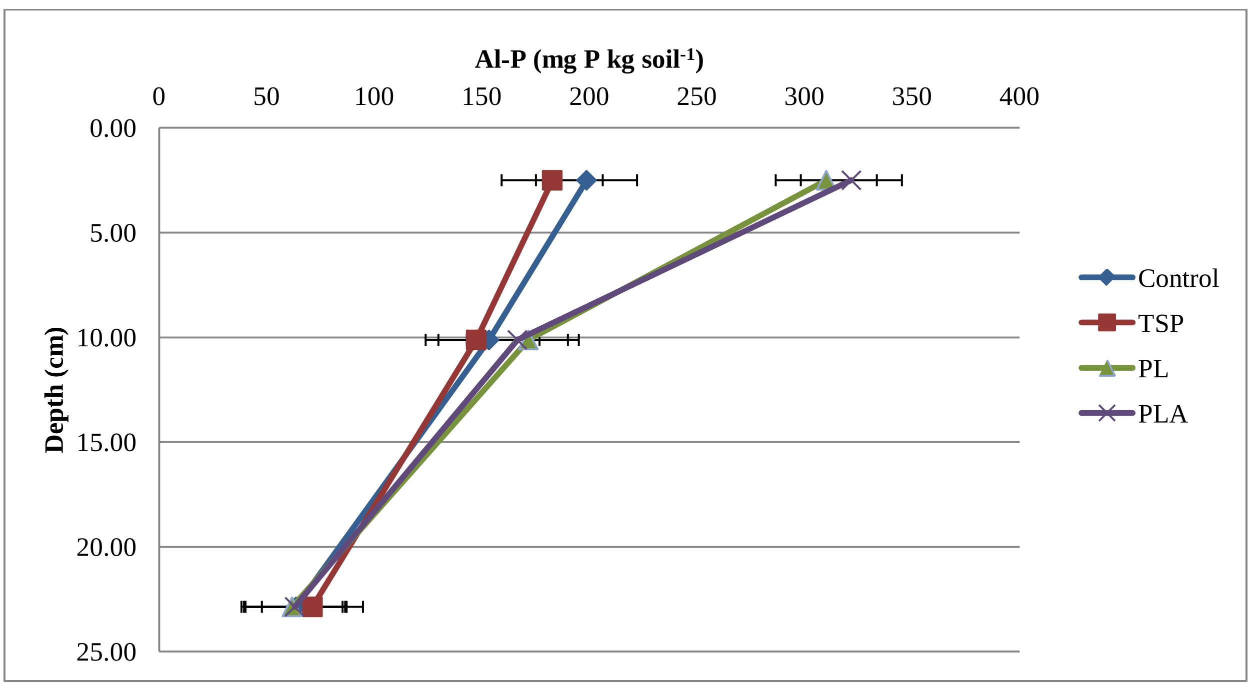

Figure 4.6. Aluminum bound P concentrations extracted via sequential fractionation on soil samples taken at depth (0-5, 5-15, 15-30 cm) in 2011 ($LSD_{0.10}$ = 47) from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

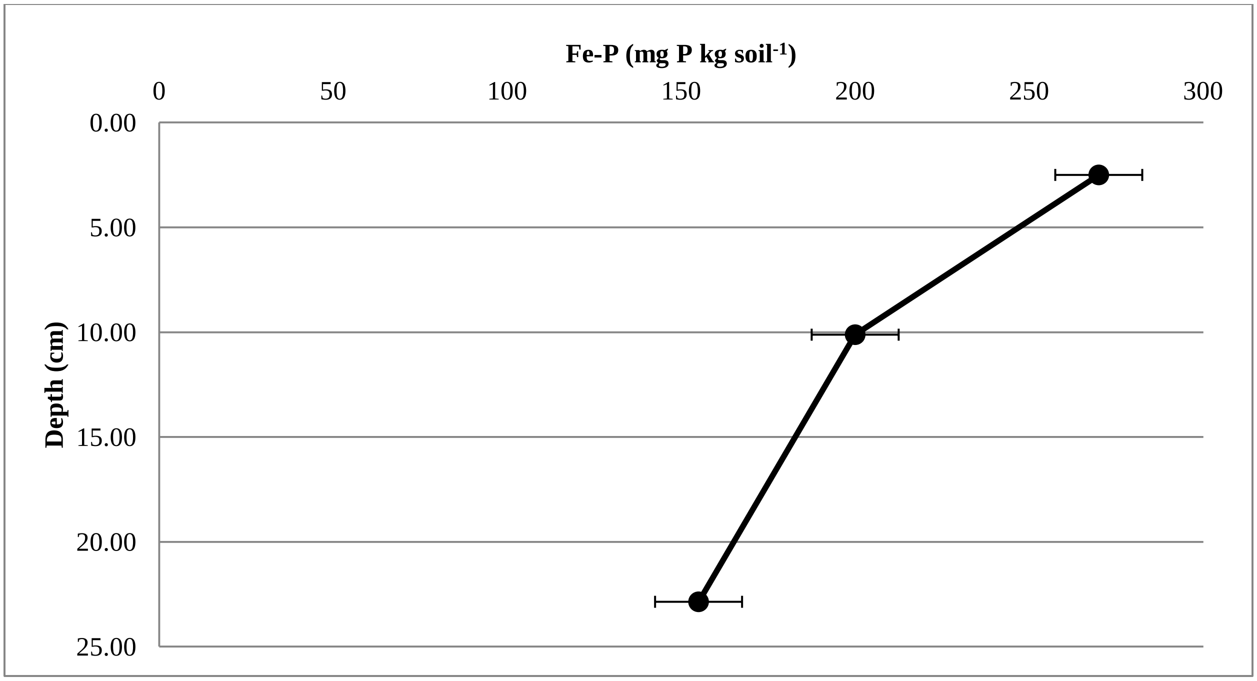

Figure 4.7. Iron bound P concentrations extracted via sequential fractionation on soil samples taken at depth (0-5, 5-15, 15-30 cm) in 2011 ($LSD_{0.10}$ = 25) averaged over treatments in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

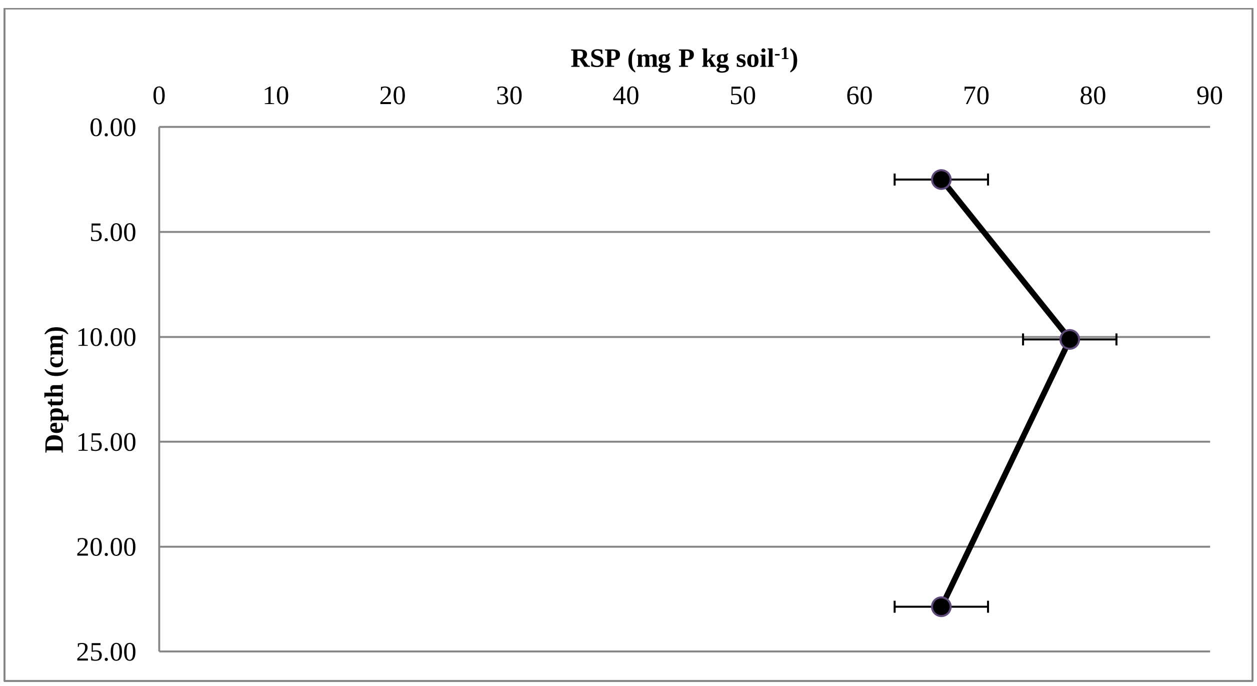

Figure 4.8. Reductant soluble P (RSP) concentrations extracted via sequential fractionation on soil samples taken at depth (0-5, 5-15, 15-30 cm) in 2011 ($LSD_{0.10}$ = 8) averaged over treatments in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

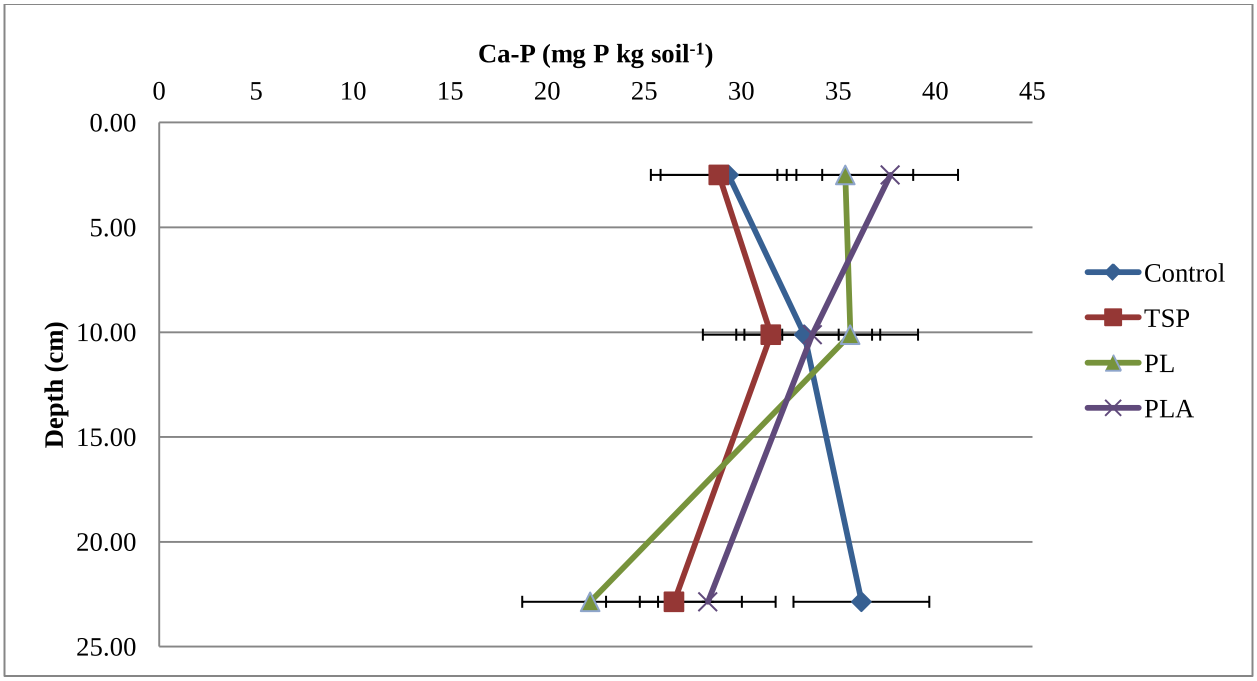

Figure 4.9. Calcium bound P concentrations extracted via sequential fractionation on soil samples taken at depth (0-5, 5-15, 15-30 cm) in 2011 ($LSD_{0.10}$ = 7) from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

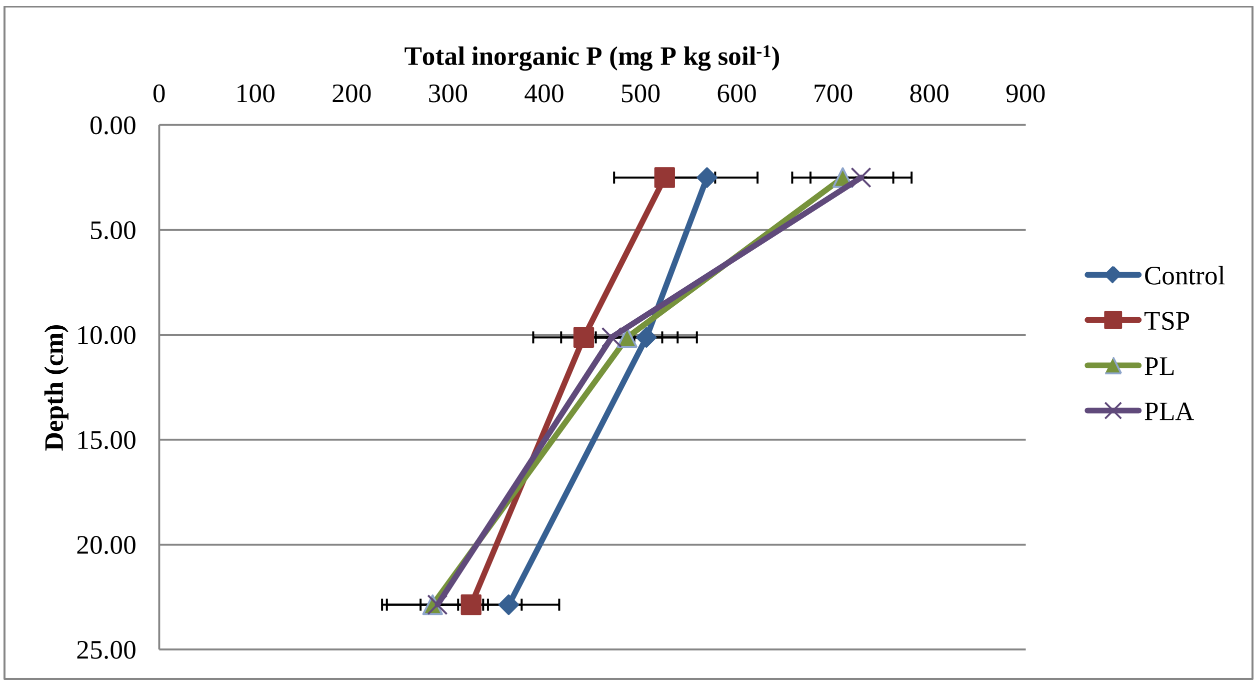

Figure 4.10. Total inorganic P concentrations (estimated by summation of the fractions) on soil samples taken at depth (0-5, 5-15, 15-30 cm) in 2011 ($LSD_{0.10}$ = 105) from four fertilizer regimes (Table 4.1) in a long-term no-till rotation on a Bojac sandy loam on the Delmarva peninsula.

5. Conclusions

Nutrient management in the Mid-Atlantic region is important due to the area's significant crop production and concentrated poultry production. The coarse textured soils in the Mid-Atlantic region's coastal plain have a high propensity to leach nutrients. Reductions of N and P losses via leaching and runoff are necessary to control acceleration of eutrophication in the Chesapeake Bay watershed. This dissertation focused on irrigation and nitrogen management of fresh market tomatoes grown on polyethylene mulch and P movement and fraction associations in soil under a long-term no-till crop rotation with organic and inorganic P sources. The data will provide information to update Virginia commercial recommendations for irrigation, N rate, and N application method for fresh market tomato systems using polyethylene mulch and drip irrigation. Additionally, data will provide information on P drawdown in unfertilized soil over time, and P behavior upon long-term additions of PL and PLA and subtractions via crop removal on no-till soils.

Irrigation management of fresh market tomatoes grown with drip irrigation is more precise than traditional seepage irrigation practices used in Florida. The evaluation of irrigation via drip tubing was evaluated in six field seasons. Evapotranspiration (ET) for fresh market tomatoes grown in Virginia was calculated using historical climate data to determine water needs, and irrigation was applied at rates based on the ET calculation (0.0ET, 0.5ET, 1.0ET, 1.5ET, and 2.0ET). Three additional treatments using tensiometers were programmed to irrigate at soil moisture set points of 20, 40, and 60 kPa. Results showed applications of 0.5ET repeatedly provided optimal marketable yields with minimal irrigation inputs. Additionally, we determined utilizing a tensiometer was an ideal in-situ instrument to monitor soil moisture to make adjustments to irrigation in the event of an unseasonable hot and dry growing season.

Applying 0.5ET also reduced residual inorganic soil N in the top 0.25 m, compared to 0.0ET by providing sufficient water to dissolve the fertilizer. This study determined that an irrigation rate of 0.5ET accompanied by a tensiometer provided optimal yields, reduced residual inorganic soil N, with minimal inputs. Further research is needed to quantify nitrate leaching from fresh market tomatoes grown on sandy loam soils.

Virginia commercial N fertilizer recommendations need to be updated to account for current agricultural practices. A field study applying 4 N rates (112, 224, 336, and 448 kg N ha^{-1}) at 2 application methods (banded and incorporated), plus a 0-N control was implemented in three seasons. The application methods represented those currently recommended in Virginia (incorporated), and in Florida (banded). Marketable yields were maximized at N rates ranging from 184 to 219 kg N ha^{-1} for the incorporated method and 200 to 242 kg N ha^{-1} for the banded method. In an unseasonably hot and dry season, the incorporated method experienced noteworthy crop loss, while the banded method continued to provide adequate yield. Post-harvest soil samples (0.00-0.25 m) indicated no significant differences of residual inorganic N between N rate treatments using the banded method; however, the incorporated method resulted in significantly higher inorganic N concentrations. Overall, Virginia commercial N fertilizer recommendations for fresh market tomato should be updated to 200-242 kg N ha^{-1} using the banded method for optimal yields, to prevent crop loss in unseasonable years, and to minimize potential residual soil N after the growing season. Further research needs to be conducted to determine optimal petiole sap nitrate-N for fresh market tomatoes grown using drip irrigation and fertigation on sandy loam soils.

The final study conducted for this dissertation focused on the soil impacts of organic and inorganic fertilizers on a long-term no-till corn-wheat-soybean rotation. Fertilizer treatments included 1) 0-P control, 2) P via triple superphosphate based on soil test recommendations (TSP), 3) PL applied at N-based rates (PL), and 4) PL amended with alum (PLA). Soil samples taken over the course of the rotation (2000 to 2011) were analyzed for pH, soil test P (M1-P; Mehlich-1 extractable P) and sequentially extractable forms of P. Soil pH decreased in all treatments over time; however, PL and PLA resulted in significantly higher pH than the control and TSP treatments due to bases such as calcium carbonate found in litter. Soil pH at three depths, averaged over all treatments, resulted in the soil surface (0-5 cm) becoming significantly more acidic than underlying soils. This was likely due to acidifying effects of N fertilizers, acid rain, and microbial activity at the surface of no-till soils. As expected with manure applications at N-based rates, PL and PLA increased M1-P over time and were greater than the control and TSP treatments. The control treatment did not see a significant decrease in M1-P until 2011; however, M1-P concentrations were still above a concentration (>55 mg P kg^{-1}) that additions of P fertilizer may increase crop yields. The concentrations of M1-P in the control treatment indicated that sandy loam soils that are high in P will provide sufficient P for crop production for many years (>11 years in our study). In 2011, M1-P at depth indicated that PL and PLA at 5-15 cm had higher concentrations of P than the control and TSP treatments at 0-5 and 5-15 cm. The increase in P at a deeper depth indicated vertical movement of P downward through the profile due to N-based manure applications exceeding plant P uptake. Additionally, a depth × treatment interaction revealed the PL treatment was greater in M1-P than PLA from 0-5 and 5-15 cm, indicating that the addition of alum to litter not only reduces water soluble P in the litter, but M1-P in the soil as well. Phosphorus fertilizer additions influenced concentrations of loosely bound P and aluminum bound P (Al-P) fractions the greatest at 0-5 cm. PL and PLA contained greater concentrations of loosely bound P and Al-P fractions than the TSP and control treatments. As seen in M1-P concentrations, PLA reduced loosely bound P compared to PL (0-5 cm); however, PLA did not generally increase Al-P associations when compared to non-amended PL.

The studies reported in this dissertation investigated irrigation and N and P fertilizer variables and resulting environmental concerns for said practices in the Mid-Atlantic. The results offer insight on efficient and productive irrigation and N fertilizer practices for fresh market tomatoes and the behavior of P via additions of PL and PLA on a long-term no-till rotation. Results for fresh market tomato production offer recommendations for optimal yields with minimal losses to the environment. Increasing irrigation and N fertilizer efficiency can increase profitability while being good stewards of environmental resources. Additionally, understanding soil impacts after long-term N-based manure applications is important in areas of high poultry production, like the Delmarva peninsula, to provide information in order to reduce negative environmental impacts. We believe these studies provide a strong starting point for implementation of irrigation and fertilizer best management practices (BMPs) for growers in the Mid-Atlantic region to decrease possible agricultural nonpoint source pollution, reduce fertilizer and water waste, and protect the tributaries and the Chesapeake Bay watershed.

6. Appendix.

Table 6.1. Temperature and extraterrestrial solar radiation values used in the Hargreaves equation to calculate reference evapotranspiration (ET_o) for Painter, Virginia.

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Average Max Temp (°C)	8.3	9.9	14.1	19.0	23.8	27.9	30.4	29.4	26.5	21.1	14.6	10.9
Average Min Temp (°C)	-1.1	-0.2	3.3	7.7	12.8	17.6	20.4	19.5	16.1	10.2	4.6	1.4
Average Temp (°C)	3.6	4.9	8.7	13.3	18.3	22.8	25.4	24.5	21.3	15.6	9.6	6.1
R_a†	16.2	21.5	28.1	35.2	39.9	41.8	40.8	37.0	30.7	23.6	17.5	14.8
ET_o (mm day^{-1})	2.45	3.57	5.63	8.49	11.00	12.54	12.82	11.34	8.90	5.97	3.49	2.51

†R_a (extraterrestrial solar radiation) based on 38°N latitude (Allen et al., 1998); Painter, VA is 37.5°N.

Table 6.2. Calculated specific crop evapotranspiration (ET_c) for initial growth stage using reduced K_c value for Painter, Virginia ($K_{c\ ini}$† = 0.60; 0.65$K_{c\ ini}$ = 0.39).

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
ET_o (mm day^{-1})	2.45	3.57	5.63	8.49	11.00	12.54	12.82	11.34	8.90	5.97	3.49	2.51
$ET_{c\ ini}$‡ (mm day^{-1})	0.95	1.39	2.19	3.31	4.29	4.89	5.00	4.42	3.47	2.33	1.36	0.98

†$K_{c\ ini}$ = Crop coefficient for initial growth stage.

‡$ET_{c\ ini}$ = Crop evapotranspiration for initial growth stage using 0.65Kc.

Table 6.3. Calculated specific crop evapotranspiration (ET_c) for crop development growth stage using reduced K_c value for Painter, Virginia ($K_{c\ CD}$† = 0.80; $0.65K_{c\ CD}$ = 0.52).

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
ET_o (mm day^{-1})	2.45	3.57	5.63	8.49	11.00	12.54	12.82	11.34	8.90	5.97	3.49	2.51
$ET_{c\ CD}$ ‡ (mm day^{-1})	1.27	1.86	2.93	4.41	5.72	6.52	6.66	5.90	4.63	3.11	1.81	1.31

†$K_{c\ CD}$ = Crop coefficient for crop development growth stage.

‡$ET_{c\ CD}$ = Crop evapotranspiration for crop development growth stage.

Table 6.4. Calculated specific crop evapotranspiration (ET_c) for mid-season growth stage using reduced K_c value for Painter, Virginia ($K_{c\ mid}$† = 1.05; $0.69K_{c\ mid}$ = 0.72).

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
ET_o (mm day^{-1})	2.45	3.57	5.63	8.49	11.00	12.54	12.82	11.34	8.90	5.97	3.49	2.51
$ET_{c\ mid}$ ‡ (mm day^{-1})	1.77	2.59	4.08	6.15	7.97	9.09	9.29	8.22	6.45	4.33	2.53	1.82

†$K_{c\ mid}$ = Crop coefficient for mid-season growth stage.

‡$ET_{c\ mid}$ = Crop evapotranspiration for mid-season growth stage.

Table 6.5. Plant nitrogen concentrations for fresh market tomato plants grown on a sandy loam soil in Painter, VA in 2009, 2010, and 2011.

	2009		2010		2011	
Treatment	Spring	Fall	Spring	Fall	Spring	Fall
	---g N kg dry plant material^{-1}---					
0.0ET	-	36.33	33.71 a†	35.47	29.04	39.15
0.5ET	25.33	36.97	30.81 a	37.58	24.18	39.06
1.0ET	22.74	34.75	24.77 bc	34.95	28.78	42.24
1.5ET	22.93	33.81	21.47 cd	38.74	25.88	38.28
2.0ET	-	35.45	19.06 d	37.58	24.71	37.82
Tens20‡	-	-	26.76 b	38.61	24.96	37.87
Tens40	-	34.40	20.53 d	36.90	24.98	36.43
Tens60	-	-	24.71 bc	36.20	27.50	37.85
P value	0.4066	0.4713	<0.0001	0.8831	0.2409	0.8961

†Means followed by different letters within a column are significantly different (p<0.10).
‡Tensiometer treatments set at 20, 40, and 60 kPa, respectively.

Table 6.6. Total plant N uptake in vegetative plant material for fresh market tomato plants grown on a sandy loam soil in Painter, VA.

	2009		2010		2011	
Treatment	Spring	Fall	Spring	Fall	Spring	Fall
	----------kg N ha^{-1}----------					
0.0ET	-	122.21	126.21	76.18	79.01	119.15
0.5ET	59.94	154.79	68.21	91.27	60.35	114.45
1.0ET	59.00	127.49	68.67	84.02	75.31	119.55
1.5ET	40.16	124.20	90.52	104.33	65.58	94.84
2.0ET	-	116.36	68.81	71.56	76.82	113.80
Tens20‡	-	-	96.89	89.10	51.61	112.53
Tens40	-	159.69	75.70	80.82	71.41	86.71
Tens60	-	-	64.65	72.77	77.07	130.91
P value	0.1342	0.3531	0.4016	0.7840	0.7621	0.5142

†Means followed by different letters within a column are significantly different (p<0.10).

‡Tensiometer treatments set at 20, 40, and 60 kPa, respectively.

Table 6.7. Fruit nitrogen concentrations for fresh market tomato plants grown on a sandy loam soil in Painter, VA.

	2009		2010		2011	
Treatment	Spring	Fall	Spring	Fall	Spring	Fall
	$g\ N\ kg\ dry\ fruit\ material^{-1}$					
0.0ET	-	50.03	45.47	46.70 c†	45.49	53.85
0.5ET	43.56	53.30	44.64	47.15 c	47.59	48.17
1.0ET	41.93	51.33	46.03	48.18 bc	45.87	48.97
1.5ET	40.73	50.77	47.92	49.72 abc	43.88	50.14
2.0ET	-	52.16	47.71	48.49 bc	45.81	55.81
Tens20‡	-	-	44.97	51.21 ab	45.29	53.05
Tens40	-	53.68	48.24	52.47 a	46.70	53.43
Tens60	-	-	48.74	50.89 ab	47.94	55.20
P value	0.4329	0.2187	0.5530	0.0744	0.9694	0.1011

†Means followed by different letters within a column are significantly different (p<0.10).

‡Tensiometer treatments set at 20, 40, and 60 kPa, respectively.

Table 6.8. Total N concentrations of soil at depth sampled after tomato growing season on a sandy loam soil in Painter, VA.

Treatment	2009 Spring	2009 Fall	2010 Spring	2010 Fall	2011 Spring	2011 Fall
	----------------	----------------	----------g N kg soil^{-1}	----------	----------------	----------------
			0.00 – 0.25 m depth			
0.0ET	-	0.36 c†	0.55	0.52	0.56	0.49
0.5ET	0.38	0.42 a	0.54	0.49	0.58	0.50
1.0ET	0.40	0.36 c	0.52	0.49	0.52	0.48
1.5ET	0.42	0.34 c	0.50	0.52	0.52	0.46
2.0ET	-	0.38 bc	0.47	0.45	0.49	0.45
Tens20‡	-	-	0.50	0.49	0.54	0.49
Tens40	-	0.41 ab	0.53	0.47	0.53	0.54
Tens60	-	-	0.54	0.46	0.51	0.54
P value	0.1983	0.0244	0.2365	0.2885	0.4848	0.3788
			0.25 – 0.50 m depth			
0.0ET	-	0.31	0.43	0.38	0.42	0.36 c
0.5ET	0.32	0.30	0.43	0.38	0.44	0.40 ab
1.0ET	0.30	0.30	0.39	0.38	0.37	0.41 ab
1.5ET	0.30	0.26	0.42	0.41	0.42	0.42 a
2.0ET	-	0.32	0.38	0.36	0.40	0.37 bc
Tens20‡	-	-	0.40	0.43	0.45	0.34 c
Tens40	-	0.25	0.44	0.39	0.39	0.38 abc
Tens60	-	-	0.40	0.38	0.37	0.42 a
P value	0.6602	0.1900	0.5764	0.2778	0.2169	0.0312
			0.50 – 0.75 m depth			
0.0ET	-	0.26	0.27	0.21	0.29	0.25
0.5ET	0.25	0.25	0.25	0.22	0.31	0.30
1.0ET	0.24	0.20	0.29	0.33	0.23	0.26
1.5ET	0.18	0.23	0.23	0.30	0.28	0.26
2.0ET	-	0.24	0.23	0.21	0.22	0.32
Tens20‡	-	-	0.22	0.31	0.33	0.29
Tens40	-	0.24	0.27	0.26	0.29	0.33
Tens60	-	-	0.25	0.26	0.22	0.24
P value	0.1715	0.4562	0.3868	0.1337	0.1580	0.3176

† Means followed by different letters within a column within a specific depth are significantly different (p<0.10).

‡ Tensiometer treatments set at 20, 40, and 60 kPa, respectively.

Table 6.9. Virginia commercial production N fertilization rates for fresh market tomato grown using polyethylene mulch based on yearly publication.

Year†	Pre-plant	Side dress	Fertigate	Total
	--------------------------------------kg N ha^{-1}--------------------------------------			
2004	45	-	3 to 4, 45 kg applications	180-224
2005	45	-	3 to 4, 45 kg applications	180-224
2006	45	-	3 to 4, 45 kg applications	180-224
2007	45	-	3 to 4, 45 kg applications	180-224
2008	45-50‡	45-50	-	90-100
2009	45-50‡	45-50	-	90-100
2010	45-50‡	45-50	-	90-100
2011	56-95‡	-	101-140§	168-235
2012	56-95‡	-	101-140§	168-235

†(Bratsch et al., 2004; Bratsch et al., 2005; Kuhar et al., 2006; Kuhar et al., 2007; Kuhar et al., 2008; Kuhar et al., 2009, 2010; Wilson et al., 2011; Wilson et al., 2012)

‡For sandy loam and loamy sand soils.

§Fertigation schedule available that increases N rate as the growing season progresses based on days after planting.

Table 6.10. Total, pre-plant, and fertigated N rates for fresh market tomato plants grown on a sandy loam soil in Painter, VA.

Treatment	Total†	Pre-Plant‡	Incorporated	Banded	Fertigated
#	--------------------------------------kg N ha^{-1}--------------------------------------				
1	0	0	0	0	0
2	112	56	19	37	56
3	224	112	37	75	112
4	336	168	56	112	168
5	448	224	75	149	224
6	112	56	56	0	56
7	224	112	112	0	112
8	336	168	168	0	168
9	448	224	224	0	224

†Total = Pre-plant + Fertigated.

‡Pre-plant = Incorporated + Banded.

Table 6.11. Fertilizer application for fertigation of fresh market tomatoes by days after transplanting on a sandy loam soil in Painter, VA.

Treatment	Total Applied Fertigation	0-14 DAT†	15-28 DAT	29-42 DAT	43-56 DAT	57-77 DAT	78-98 DAT
#	----kg N ha^{-1}----	----------------------------kg N ha^{-1}----------------------------					
1	0	0.00	0.00	0.00	0.00	0.00	0.00
2, 6	56	2.62	3.64	5.21	7.82	17.20	19.53
3, 7	112	5.23	7.27	10.40	15.64	34.41	39.07
4, 8	168	7.85	10.91	15.61	23.45	51.61	58.60
5, 9	224	10.46	14.54	20.81	31.27	68.81	78.13

†DAT = Days after transplant

Table 6.12. Inorganic N concentrations (NH_3-N + NO_3-N) of 2*M* KCl extracted soil sampled after fresh market tomato growing season on a sandy loam soil in Painter, VA (year × method × rate interaction), averaged over depth.

Total N rate treatment†	2009		2010		2011	
	Banded	Incorporated	Banded	Incorporated	Banded	Incorporated
--(kg ha^{-1})--	---------- mg N kg soil^{-1} ----------					
112	4.5 i‡	4.6 i	11.1 bcde	7.4 defghi	5.6 hi	8.2 cdefghi
224	5.9 hi	6.3 ghi	7.3 defghi	6.8 fghi	8.3 cdefghi	9.1 cdefgh
336	7.1 efghi	8.6 cdefghi	11.3 bcd	14.6 b	10.9 bcdef	9.2 cdefgh
448	9.5 cdefgh	10.3 cdefg	11.9 bc	14.6 b	8.8 cdefgh	19.5 a
			$LSD_{0.10}$ = 4.1			

†0-N control treatment averaged 4.3, 6.0, and 5.9 mg N kg soil^{-1} in 2009, 2010, and 2011, respectively.
‡Means followed by different letters are significantly different (p<0.10).

Table 6.13. Normal Difference Vegetation Index (NDVI) readings for fresh market tomato plants grown on polyethylene mulch on a sandy loam soil in Painter, VA.

Total N rate treatment†	2009 Banded	2009 Incorporated	2010 Banded	2010 Incorporated	2011 Banded	2011 Incorporated
--(kg ha^{-1})--			---NDVI---			
112	0.94	0.94	0.88	0.83	0.91	0.88
224	0.94	0.94	0.87	0.83	0.93	0.87
336	0.93	0.92	0.88	0.87	0.91	0.88
448	0.94	0.86	0.82	0.88	0.89	0.91
P value‡	ns§	0.0177	0.0066	0.0523	0.0089	0.0380

NDVI Response¶	2009	2010	2011
Banded	ns	$(-3\times10^{-6})N^2 + 0.0009N + 0.8119$	$(-2\times10^{-6})N^2 + 0.0008N + 0.8549$
Incorporated	$(-1\times10^{-6})N^2 + 0.0004N + 0.9173$	$(2\times10^{-7})N^2 + 0.0002N + 0.8086$	$0.0001N + 0.8549$

†0-N control treatment averaged 0.92, 0.81, and 0.85 in 2009, 2010, and 2011, respectively.
‡P value for regression equation.
§Not significant.
¶ Highest order model (linear or quadratic) that was significant presented.

Table 6.14. Plant nitrogen concentrations for fresh market tomato plants grown on polyethylene mulch on a sandy loam soil in Painter, VA.

Total N rate treatment†	2009		2010		2011	
	Banded	Incorporated	Banded	Incorporated	Banded	Incorporated
--(kg ha^{-1})--	g N kg dry plant $material^{-1}$					
112	25.87	22.55	23.82	24.76	21.77	19.62
224	24.49	26.04	28.64	30.57	23.55	22.47
336	30.27	28.68	31.06	34.27	24.89	25.70
448	28.85	29.95	29.96	36.42	25.14	27.45
P value‡	0.0219	0.0014	0.0419	0.0126	0.0002	<0.0001

Plant N Response§	2009	2010	2011
Banded	$(-4\times10^{-6})N^2 + 0.0174N + 23.479$	$(-8\times10^{-5})N^2 + 0.0541N + 21.681$	$-0.0001N^2 + 0.0655N + 16.565$
Incorporated	$(3\times10^{-5})N^2 + 0.0095N + 22.814$	$(-3\times10^{-5})N^2 + 0.0559N + 21.958$	$(-3\times10^{-5})N^2 + 0.0459N + 16.186$

†0-N control treatment averaged 23.46, 22.45, and 16.24 g N kg dry plant $material^{-1}$ in 2009, 2010, and 2011, respectively.
‡P value for regression equation.
§Highest order model (linear or quadratic) that was significant presented.

Table 6.15. Total soil N concentrations sampled after fresh market tomato growing season on a sandy loam soil in Painter, VA (year × method interaction) averaged over N rate and depth.

Method	2009†	2010‡	2011§
	----------------------	g N kg soil^{-1}	----------------------
Banded	0.43 a¶	0.38 cd	0.35 e
Incorporated	0.41 ab	0.39 bc	0.36 de
		$LSD_{0.10}$ = 0.02	

†0-N = 0.40 g N kg soil^{-1}.
‡0-N = 0.35 g N kg soil^{-1}.
§0-N = 0.33 g N kg soil^{-1}.
¶Means followed by different letters are significantly different (*p*<0.10).

Table 6.16. Total soil N concentrations sampled after fresh market tomato growing season on a sandy loam soil in Painter, VA (method × depth interaction) averaged over N rate and year.

Method	0.00-0.25 m†	0.25-0.50 m‡	0.50-0.75 m§
	----------------------	g N kg soil^{-1}	----------------------
Banded	0.48 a¶	0.40 b	0.28 c
Incorporated	0.50 a	0.40 b	0.26 c
		$LSD_{0.10}$ = 0.02	

†0-N = 0.46 g N kg soil^{-1}.
‡0-N = 0.36 g N kg soil^{-1}.
§0-N = 0.26 g N kg soil^{-1}.
¶Means followed by different letters are significantly different (*p*<0.10).

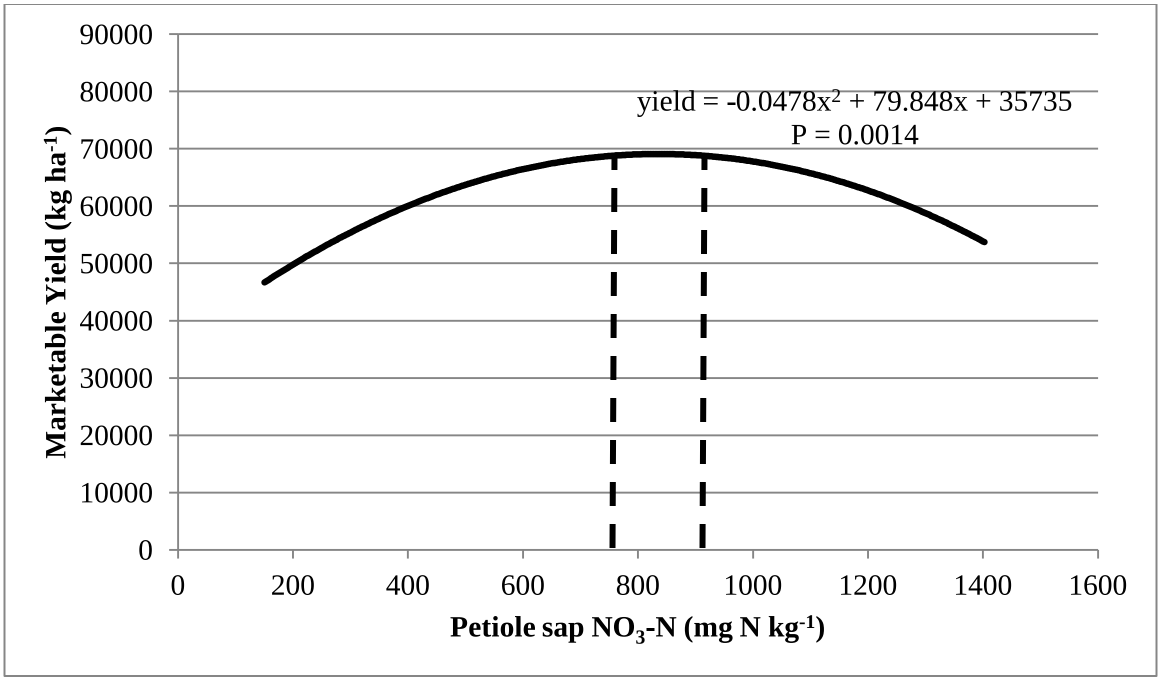

Figure 6.1. Petiole sap nitrate-N versus marketable yield (2009) and confidence interval 751 – 919 mg NO_3-N kg^{-1} for fresh market tomatoes grown on polyethylene mulch on a sandy loam soil in Painter, VA.

References

Allen, R., L. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - guidelines for computing crop water requirements, Irrigation and drainage paper 56, FAO, Rome.

Bratsch, A.D., T.P. Kuhar, S.B. Phillips, S.B. Sterrett, C.M. Waldenmaier, and H.P. Wilson. 2004. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Bratsch, A.D., T.P. Kuhar, S.B. Phillips, S.B. Sterrett, C.M. Waldenmaier, H.P. Wilson, et al. 2005. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2009. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2010. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, J.H. Freeman, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2008. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., H.B. Doughty, S.B. Phillips, R.A. Straw, C.M. Waldenmaier, S.L. Rideout, et al. 2007. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Kuhar, T.P., S.B. Phillips, R.A. Straw, C.M. Waldenmaier, and H.P. Wilson. 2006. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Wilson, H.P., T.P. Kuhar, S.L. Rideout, J.H. Freeman, M.S. Reiter, R.A. Straw, et al. 2012. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.

Wilson, H.P., T.P. Kuhar, S.L. Rideout, J.H. Freeman, M.S. Reiter, R.A. Straw, et al. 2011. Commercial vegetable production recommendations - Virginia. Virginia Coop. Ext., Blacksburg, VA.