PELLETIZED POULTRY LITTER AS A NUTRIENT SOURCE FOR TURFGRASS SPORTS FIELDS

by

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A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Plant and Soil Sciences

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ABSTRACT

An increasing interest in recreational sports has prompted a corresponding increase in the intensity of athletic field use and management. Proper cultural practices are essential to an athletic field management program that will produce an attractive and wear-resistant playing surface. A cultural practice that is receiving increasing attention is the use of natural organic fertilizers (e.g. manure or compost) to supplement or replace synthetic fertilizers. The primary objective of this study was to evaluate turfgrass response to the use of pelletized poultry litter (PPL) as a nutrient source and to compare core aeration and vibrating aeration on three high school athletic fields. The current practice on the athletic fields is to fertilize twice each year (spring and fall) using a synthetic fertilizer (total N for each growing season was 48 kg ha^{-1}) and to use core aeration. Four treatment combinations were evaluated: synthetic fertilizer and vibrating aeration (VS), synthetic fertilizer and core aeration (CS), PPL and vibrating aeration (VP), and PPL and core aeration (CP). The PPL (4-2-3 analysis) was applied at a nitrogen (N) rate equivalent to the synthetic fertilizer (assuming 50% availability of N). Soil and turfgrass samples, multi-spectral remote sensing, and soil penetrometer readings were taken prior to the start of the study, and before the application of each treatment.

The use of PPL did not result in any significant changes in measured soil parameters during the 2.5 year study compared to the synthetic fertilizer. This is likely because soil nutrients were applied at nearly equivalent rates, but could also be due to the relatively short duration of the study. Soil sampling indicates that plant nutrients were supplied in adequate amounts. Tissue concentrations of Mn were

affected by treatment; the VS treatment had the largest Mn increase over time. However, this increase of Mn was minimal. The synthetic fertilizers used during the fall and spring applications did not contain Mn. Remote sensing results indicate that fertilizer efficiency varies with aeration method used. The current management practice at St. Andrew's School (CS) produced the lowest turfgrass quality of all the treatments. Highest turf quality was achieved with the CP and VS treatments. Application of PPL resulted in greater turfgrass quality when compared to the same N rate of synthetic fertilizer, regardless of aeration method.

A mineralization study was also performed to determine the amount of plant available (PAN) from PPL. Using a Matapeake silt loam soil, eight treatment combinations, each with three replications, were evaluated over a period of 98d. The PPL was applied at rates of 0, 48, 146, and 244 kg N ha^{-1} and either incorporated (mixed) or topdressed (not-mixed) into the soil. Results show that under laboratory conditions PAN of PPL ranges from 43% to 55% (LSD=5.8%). This indicates that 50% PAN is an appropriate estimate for PPL. However, data suggest that mixing PPL into the soil results in a higher, although not significant, percentage of PAN.

CHAPTER 1

LITERATURE REVIEW

1.1 Nutrient Issues Related to Poultry Production in Delaware

Delaware is located in the eastern section of the Delmarva Peninsula (Delaware¸ Maryland, and Virginia). The total area of Delaware is 6,206 square kilometers with a land area of 5,061 square kilometers (U.S. Census Bureau, 2002). Delaware has a strong agricultural industry. In 2007, the total market value of agricultural products sold was more than $1 billion; grain crops and poultry production being the two major contributors to agricultural receipts (USDA, 2008). There are approximately 2,546 farms in Delaware, 54% of which are located in Sussex County (USDA, 2008). Most of these farms (918) are either in poultry production or grain crop production to supply poultry operations (USDA, 2008). The 2007 Census of Agriculture reported that the state of Delaware sold 246,098,878 broilers and other meat type chickens, ranking 8th in the United States, and Sussex County is the number one broiler-producing county (USDA, 2008).

In Delaware, poultry (*Gallus gallus domesticus*) are raised on concrete, wood, or earth floors with a 5 to 15 cm layer of an absorptive base; commonly sawdust or wood shavings (Collins, 1996). The manure and bedding mixture, referred to as litter, is completely removed from the poultry house on a cycle that varies from one to five years. It is estimated that for every 1,000 birds, 1.1 tonnes of litter is generated on an annual basis (Lichtenberg et al., 2002). One poultry house contains 20,000 to 25,000 chickens per flock and produces five to six flocks per year. This quantity of birds will produce 113 to 136 tonnes of litter that must be properly stored, land applied, or transported off the farm for an alternative use (Paudel and McIntosh, 2005). Based on these numbers, Delaware produced approximately 267,909 tonnes of poultry litter in 2007.

Poultry litter is commonly applied to agricultural fields based on plant nitrogen (N) requirements (Preusch et al., 2002). Because poultry litter has almost an equal concentration of N and phosphorus (P), P is often applied in excess of plant requirements, resulting in an accumulation of P in the soil (Maguire et al., 2005). Excess P can remain in the soil, leach downward through the soil profile into groundwater, or wash into nearby surface waters thereby becoming a nonpoint source of pollution (McGrath et al., 2005). After decades of consistently land applying the poultry litter to the same fields, which are typically sandy, acidic, and have low nutrient holding capacity, soil test P values in Delaware commonly exceed the optimum amount needed for plant growth, causing increased loss of P to surface waters (Delaune et al., 2004). Although P losses from agricultural land usually are not important agronomically, they can have serious environmental consequences (Pote et al., 1999).

Nutrients entering water systems are of great concern in Delaware (Waite et al., 2000). Nitrogen is a human health concern because of nitrates in groundwater and drinking water. Both N and P are an environmental concern; P is more often the limiting factor in algal growth in fresh water and N is the limiting nutrient responsible for algal blooms in coastal estuaries (Robinson and Sharpley, 1995; Easton and Petrovic, 2004). Soils that contain high levels of P can become a source of dissolved reactive P (DRP) in runoff, and contribute to eutrophication of surface waters (Volf et al., 2007). Eutrophication is an over-enrichment of a water body with nutrients causing excessive aquatic plant growth; the aquatic “weeds” block incoming sunlight to the water body, resulting in plant decomposition causing a reduction in oxygen levels, triggering fish kills. Eutrophic water bodies pose further risks and restrictions for fisheries, recreation, industry, and drinking water due to the undesirable aquatic weeds and odor.

To address these water quality issues, Delaware passed a law in June of 1999, the Delaware Nutrient Management Act. This Act requires individuals who land apply nutrients (N and P) to develop a nutrient management plan (Binford and Hansen, 2002). Such plans often result in restrictions in land application of poultry litter. Poultry producers are solely responsible for proper disposal of the litter and fear that these regulations will result in excess litter for which they have no use (Paudel and McIntosh, 2005; Lichtenberg et al. 2002). Delaware has a poultry litter relocation program that provides poultry producers cost assistance for transporting poultry litter to other farms that are in need of nutrients or for alternative uses (DNM, 2008).

One alternative to land application of poultry litter is to pelletize it and use it as a fertilizer source. Currently, there is a pelletizing plant in Seaford, DE, operated and owned by Perdue® AgriRecycle™. The process of creating the pelletized poultry litter (PPL) begins on the farm. Perdue® AgriRecycle™ (2001) has signed contracts with poultry producers in Delaware and the surrounding area that allow the company to remove surplus litter from their farm. Once the poultry litter is in the plant it is pasteurized and dried (which destroys bacteria and weed seeds), and pelletized. Perdue® AgriRecycle™ (2006) produces approximately 45,359 tonnes of PPL per year. This product is certified by the Organic Materials Review and marketed as

MicroStart60Plus™ fertilizer with a 4-2-3 nutrient analysis. The product also includes calcium (Ca), magnesium (Mg), and iron (Fe). It is low in salt, free of contaminants, and has a carbon (C) to N ratio of 12:1 (Perdue® AgriRecycle™, 2006). Because PPL is free of pathogens and certified organic, it is safe to apply around people and animals, making it the perfect fertilizer for recreational and athletic turfgrass fields.

Turfgrass produces tightly knit roots and thatch that create an extremely efficient nutrient filter (Easton and Petrovic, 2004). Research has shown that proper application of animal manures on turfgrass positively effects turfgrass quality and has limited environmental consequences. For example, Edwards and Daniel (1994) reported that synthetic fertilizer produced higher runoff concentrations of NO_3-N, NH_4-N, orthophosphate (PO_4-P), and total P than poultry litter when applied to fescue. Gaudreau et al. (2002) reported similar results in bermudagrass [*Cynodon dactylon* (L.) Pers. Var. Guymon] treated with inorganic fertilizers and dairy manure.

Soil physical and chemical properties resulting from manure applications were studied by Johnson et al. (2006). They reported that topdressing established Kentucky bluegrass (*Poa pratensis* L.) with various rates of composted organic dairy cattle manure resulted in decreased bulk density and increased moisture retention with increasing rates of compost, and provided sufficient nutrient concentrations without increasing nutrient runoff. Nyakatawa et al. (2001) reported that applications of poultry litter increased soil organic matter as much as 55% when compared with an inorganic fertilizer. Both Nyakatawa et al. (2001) and Kingery et al. (1994) found increased soil organic matter due to application of poultry litter to the top 15 cm of the soil. Codling et al. (2002) suggested that poultry litter was a reasonable option for use as a P nutrient source since it resulted in low levels of water soluble P and metals in soil and low levels of metals in the plant. However, other studies note that poultry litter also contains Fe, Cu, Mn, Zn, and arsenic (As) that can potentially accumulate in the surface horizons of soils receiving annual applications of poultry litter (Jackson et al., 2003; Franzluebbers et al., 2004; Tewolde et al., 2005).

Many studies suggest that while nutrients in composted cattle manure and/or poultry litter may be less soluble and less available to plants, nutrient losses are low when used properly, and soil organic matter increases with manure additions. Soil organic matter is an indicator of soil health; water infiltration, water holding capacity, nutrient cycling, and pesticide absorption all increase with increasing soil organic matter content (Ding et al., 2002).

1.2 Turfgrass Growth and Physiology

The turfgrass plant is a low growing monocot that differs greatly from typical dicotyledonous species in structure, pattern, and by the fact that turfgrass plants are tolerant to frequent defoliation by mowing and traffic (Turgeon, 2008). Turfgrass plants grow through tillering, stolon or rhizomatous growth, and by developing new vegetative shoots (Aldous, 1999). The plant parts that are above the soil are referred to as the shoot. The shoot includes, starting from the very tip of the plant, the inflorescence (seed head), the leaves, and the stem. The leaf is made up of two parts, the blade and the sheath; the blade is the upper flattened portion of the leaf and the sheath is the lower tubular portion of the leaf (Christians, 2004). Nodes, or enlarged areas, can be found along the stem; this is where leaves or lateral stems will grow from buds. At the very base of plant, near the soil, is the crown. Turfgrass mowing and traffic tolerances exist due to the position of the crown, the top of which is the apical meristem (Turgeon, 2008). Leaves continually arise from the crown, providing a constant covering of green shoots. However, if the crown dies, the plant dies. Older leaves, which arise near the base of the crown, eventually fall to the surface of the soil and are replaced by leaves emerging from higher on the crown, maintaining a relatively constant number of leaves per shoot (Turgeon, 2008). The crown is the epicenter of the turfgrass plant; it is the source of the leaves, roots, lateral stems, and inflorescence. Buds located at nodes along the crown can develop into tillers, stolons, or rhizomes depending on the type of grass plant. Tillers emerge from within the leaf sheaths; alternatively, the buds may give rise to horizontally growing shoots, along the surface of the soil (stolons) or the buds may form into a stem grows horizontally, below the soil surface (rhizomes) (Turgeon, 2008).

Turfgrasses are further divided into cool season and warm season species. As the names state, cool season grasses grow well in cooler temperatures. They enjoy the cool humid, cool sub-humid, and cool semiarid regions of the world; cool season grasses also do well in the transition zone (average 27°N latitude and 322 km width). Examples of cool season grasses are bluegrasses, fescues, and ryegrasses. Optimal air temperatures for cool season grasses are between 17 and 24°C with soil temperatures between 10 and 18°C (Aldous, 1999). Cool season turfgrasses typically show a bimodal growth pattern (Turgeon, 2008); they show rapid growth during the cool, moist periods of the year and typically become quiescent during the warm to hot summers (Aldous, 1999). Therefore, cool season turfgrasses provide a good surface cover over autumn and winter, but are not ideal for the summer.

Turfgrasses are plants that “form a uniform layer that tolerates regular mowing and foot traffic” (Turgeon, 2008). Turfgrass is used for a variety of purposes; Turgeon (2008) has divided turfgrass into utility turf, lawn turf, and sports turf according to increasing usage. Sports turfgrass, such as that found on athletic fields, serves as a source of pleasure for participants and observers. Player safety is substantially enhanced by the soft cushion provided by turfgrasses on a soil base that can be very hard during dry conditions (Turgeon, 2008). Management requirements of athletic field turfgrass systems are unique due to intense and constant use, which causes soil compaction (Turgeon, 2008).

Turfgrass also provides a number of environmental benefits including air cooling (from transpiration), absorbing toxic roadside emissions, and reducing dust. This reduction in dust prolongs the engine life of airplanes. Large quantities of rainfall are captured and retained in turfgrass systems, thereby reducing the rate and volume of surface runoff, as well as reducing the amount of nutrients and pesticides lost to surface waters (Balogh and Walker, 1992; Waite et al., 2000). A dense growth habit, and tight interconnecting system of fibrous roots, bonds soil to the turfgrass roots, reducing soil loss from both water and wind (Turgeon, 2008).

1.3 Turfgrass Quality

The quality of athletic field turfgrass is defined by its utility, appearance, and playability during the growing season (Turgeon, 2008). It should stabilize the soil, look attractive (i.e. thick and green), and must be wear-resistant and have strong recuperative abilities. Parents and players alike enjoy watching and playing on a healthy turf; a dark green color is attractive, and the uniform dense growth provides traction and cushioning for the players.

Factors affecting turfgrass quality are density, texture, uniformity, color, growth habit, and smoothness (Turgeon, 2008). Density refers to the thickness of the turfgrass or, more specifically, the number of aerial shoots per unit area. Genetics and environmental factors play a dominant role in density as well as cultural management. Bentgrasses, bermudagrasses, and greens-type annual bluegrasses have the highest turfgrass densities obtainable (Turgeon, 2008). Texture is a measure of leaf blade width. Narrow leaves signify fine textured turfgrasses (e.g. red fescue and rough bluegrass). Broad leaf blades characterize coarse textured turfgrasses such as tall fescue. Usually fine- and coarse-textured turfgrasses are not planted together because the resulting turfgrass would not look uniform. Density and texture are related features in that as density increases, texture becomes finer.

Uniformity is an estimation of the even appearance, or consistency, of a turfgrass within a given field (Turgeon, 2008). Turfgrass is considered uniform if the shoots have the same shape, size, and orientation; a weed invasion would result in low uniformity. Unlike density and texture, uniformity is tedious to measure with traditional (manual) techniques.

Color is a measure of the light reflected by turfgrass; different species and cultivars vary in color from light to very dark green (Turgeon, 2008). These differences are usually more visible in the early and late portions of the growing season. Color is a useful indicator of the general condition of the plants. A yellow, or chlorotic, appearance may indicate nutritional deficiencies (e.g. N), disease, or some other unfavorable factor influencing turfgrass growth. An unusually dark color may be evidence of over fertilization, wilting, or the early stages of a disease. Mowing can also influence the color of turfgrass. Improperly mowed turfgrass with ragged leaf ends may appear gray to brown at the surface. The use of a sharp, properly adjusted mower can easily correct this problem. The direction of mowing can affect the color of the turfgrass, as well. Striping, or mowing the turfgrass in bands, will yield light and dark stripes.

Each type of turfgrass offers a distinctly different visual appearance. Growth habit describes the type of shoot growth evident in a particular turfgrass. The three basic types of growth habit are bunch-type, rhizomatous, and stoloniferous (Turgeon, 2008). The bunch-type grasses spread primarily by tillering as a gradual increase in clump size. They can form a uniform turf if seeded at a sufficient rate. However, at low seeding rates small clumps develop, resulting in an uneven surface. "Clumpiness" in a turf is characteristic of perennial ryegrass, tall fescue, annual bluegrass, and other bunch-type grasses. Rhizomatous turfgrasses spread by underground stems called rhizomes. Because of the emergence of rhizome terminals at positions away from the mother plant, strongly rhizomatous turfgrasses tend to form a uniform canopy with aerial shoots oriented in a generally upright position (Turgeon, 2008). Rhizomatous turfgrasses are very tightly bound to each other and difficult to tear from the ground. Stoloniferous turfgrasses spread by aboveground stems, called stolons, and may appear to bend toward the ground.

Smoothness is a surface feature of turfgrass that affects both visual quality and playability. Smoothness is extremely important to the playability of some sports, such as field hockey, because it affects ball roll speed; ragged turfgrass blades would lessen the speed of the ball.

The functional quality of a turf is not only determined by visual characteristics, but by other less easily defined characteristics such as rigidity, elasticity, resiliency, yield, verdure, roots, and recuperative capacity (Turgeon, 2008). Rigidity refers to the resistance of the turfgrass leaves to compression and is related to the wear resistance of turfgrass; a very rigid turfgrass will allow a ball to sit on the tips of the turfgrass canopy versus a less rigid turfgrass in which the ball would bend and compress the leaf blades. Rigidity is influenced by the chemical composition of the plant tissue, water content, temperature, plant size, and density. Zoysiagrasses and bermudagrasses form very rigid turfs of excellent wear resistance while Kentucky bluegrasses and perennial ryegrass form less rigid and less wear-resistant turfs (Turgeon, 2008). Softness is the opposite of rigidity. Given sufficient wear resistance, softness may be a desirable feature of some turfs depending on the intensity and type of use.

Elasticity is the flexibility of the turfgrass or the amount of “spring.” Elasticity is an essential property because without it turfgrass would lie flat to the ground after a person or machine trod on it (Turgeon, 2008). When turfgrass is frozen or frosted over, the water inside the plant tissue is frozen as well. If a person or equipment moves over the turfgrass while it is frozen the turf will be damaged. It is necessary to halt all activities on turfgrass until the frost disappears. Elasticity will naturally increase as diurnal temperatures increase.

Resiliency is the capacity of a turf to absorb shock and is largely a feature of the medium in which the turfgrass is growing (Turgeon, 2008). Soil texture and structure are important contributing factors. Layers of thatch substantially increase resiliency.

Yield is a measure of growth, or the amount of clippings removed with mowing. It is an indication of turfgrass growth, and indirectly health, as influenced by fertilization, irrigation, and other management practices as well as natural environmental factors. In experimental plots, clippings are first dried at 40.6°C for at least three hours, and then weighed to provide yield data (Turgeon, 2008). On golf courses, superintendents often measure yield in number of baskets of clippings removed. This method provides a quick estimate of tissue growth. However, the objective of most turfgrass superintendents and athletic field managers is not to produce high amounts of turfgrass, this only promotes more mowing which means more labor; more time, and more money. Field managers are more interested in quality of turfgrass than quantity of turfgrass.

Verdure is a measure of aerial shoots remaining after mowing. Within a particular turfgrass genotype, increasing verdure is correlated with increasing resiliency and rigidity (Turgeon, 2008). The amount and appearance of plant material comprising the verdure over time are indicators of visual and functional qualities of a turf.

Rooting is the amount of root growth evident at any one time during the growing season. It can be estimated visually by extracting a turf core with a soil probe and carefully separating the roots from the soil. Numerous white roots extending to a depth of several centimeters indicates good rooting in a turf. One of the main turfgrass management objectives is to develop strong root systems during favorable conditions during the spring, to maintain as much of the root system as possible during the summer, and then to generate new root growth in the fall (Turgeon, 2008).

Recuperative capacity is the ability of the turfgrass to recover from damage caused by disease organisms, insects, and traffic (Turgeon, 2008). Recuperative capacity varies with different turfgrass genotypes and is strongly influenced by management and natural environmental conditions. Factors that reduce recuperative capacity include severely compacted soils, inadequate or excessive fertility and/or moisture, extreme high or low temperatures, insufficient light, and disease (Turgeon, 2008).

1.4 Measuring Turf Quality with Optical Remote Sensing

Turfgrass quality can be defined in a number of different ways. Many of the variables used to quantify turfgrass quality are arduous and time consuming to measure, and require experienced individuals to interpret (Bell et al., 2002). Recent studies have suggested multispectral remote sensing as an efficient and effective tool to quantify turfgrass quality (Bell et al., 2002).

Plant chlorophyll is necessary for photosynthesis ($6CO_2 + 6H_2O + \text{SUNLIGHT} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$) and can be measured by degree of green reflectance, GRN, (500-600nm) with remote sensing. Low chlorophyll concentrations in leaves result in higher reflectance of GRN light. Photosynthesis is activated by the absorption of blue, B, (400-500nm) and red, R, (600-700nm) wavelengths (Trenholm et al., 1999). A healthy plant will have large quantities of chlorophyll and be actively photosynthesizing (i.e. vigorous), therefore R and GRN reflectance will be low. Plants in poor health will have less chlorophyll and be photosynthesizing less; therefore, R and GRN reflectance will be high relative to a healthy plant. Near infrared radiation, NIR, (700-800nm) reflectance increases with increasing plant structure (Bell et al., 2002). A large plant will have high NIR reflectance. Remote sensing can easily differentiate between large, vigorously-growing and small, poorly-growing plants because of the inverse relationship between GRN (or R) and NIR.

Many studies have reported a strong correlation between spectral band ratios, such as NIR/GRN, and plant quality (Campbell, 2007). As the value of this ratio increases, turfgrass quality increases. Other indices, such as the Normalized

Difference Vegetative Index (NDVI= NIR-R/NIR+R), have been correlated with the presence of large vigorously growing plants. However, soil wetness, "sun sensor surface viewing geometries," and atmospheric effects, such as thin clouds, clouds with shadows, and/or snow create noise and can significantly hinder accuracy of NDVI measurements (Campbell, 2007; Hird and McDermid, 2009). In addition, off-nadir viewing (viewing in the forward or afterward direction) and low sun zenith angles (the angle the sun makes with the ground), as well as ozone, dust, and other aerosols, decrease NIR reflectance, skewing the NVDI values (Hird and McDermid, 2009).

The NIR/GRN band ratio has been used in many studies. For example, Chang et al. (2005) used NIR/R and NIR/GRN to derive canopy reflectance measurements at booting stage that were highly correlated with small grain yields. A similar study by Xue et al. (2004) found that NIR/GRN was the most efficient ratio for predicting rice (*Oryza sativa* L.) leaf N content at various growth stages. Ramsey and Rangoowala (2005) used NIR/GRN to detect and monitor stages of marsh dieback (e.g. the browning and death) of *Spartina alterniflora* and smooth cord grass in intertidal salt marshes. The values of the NIR/GRN ratio decreased as site impact increased.

There are two spectral radiometers commonly used in agriculture; the GreenSeeker® and the Cropscan®. GreenSeeker® is an active (i.e. provides its own light source) sensor that measures reflectance from R, or amber, and NIR light (N Tech Industries, 2009). The Cropscan® is a passive sensor (i.e. utilizes sunlight) that measures eight wavelengths of light (460, 510, 560, 610, 660, 710, 770, and 810nm). It measures both incoming sunlight and reflectance from the crop canopy, thus adjusting for ambient light conditions (CROPSCAN, 2005). The size of the area sampled by both sensors is controlled by raising or lowering the height of the sensor above the target. For example, a sensor two meters above the canopy would measure the reflectance from an area one meter by one meter.

1.5 The Intense Management of Athletic Fields

1.5.1 Athletic Field Soils

Soils have various chemical, physical, and biological properties that may be either benefit or harm turfgrass growth (Carrow et al., 2001). These properties are often overlooked because turfgrass managers view soil as a physical growing medium rather than a nutrient and water reservoir for plants. This is unfortunate because many factors that determine the amount of management needed to sustain healthy turfgrass in a constant wear and tear setting are related to the soil (Carrow et al., 2001).

Athletic fields are characterized by nearly constant use of the site; it is common for a field to be used year round for a variety of sports. This means that fields are never allowed to fully recuperate. Foot traffic inflicts stresses, such as wear and tear and soil compaction, which increase over time (Carrow et al., 2001). Frequent mowing, and mowing at a low height, is another major source of stress on turfgrass because it affects the growth of the tissue and the frequent use of heavy equipment compacts the underlying soil.

Irrigation is an important management issue. Irrigation may be necessary on fields that do not receive adequate rainfall. Conversely, if fields are too waterlogged, drainage systems may be needed to remove excess water. In addition, play often occurs during, or shortly after, rain events and this can cause soil compaction.

Sand or organic material can be mixed into the soil to change the soil texture and structure, respectively. The amount of water retained by the soil depends primarily upon soil texture and this is managed by amending, or renovating, native soils. On a small scale (e.g. the top 10 cm of soil), this can be somewhat beneficial. However, it is quite difficult, and extremely expensive, to significantly change the texture of a soil. Another option is to completely remove the native soil and install a sand-based system.

Soils are very complex and differ physically and chemically at both small (within a field) and large (county or regional) scales (Adams and Gibbs, 1994). Small-scale differences are typically due to variations in soil parent material, landscape, the history of land use, or a combination of these factors (Adams and Gibbs, 1994). On a large scale, differences in climate and the age of soils can cause major variations (Adams and Gibbs, 1994).

Many turfgrass soils have been disturbed and do not possess the typical profile developed through many years of physical and chemical weathering, leaching, and microorganism activity (Beard, 1973). For example, soils around homes, buildings, and other construction sites often are completely removed and replaced with less fertile material. It is common to remove the topsoil from construction sites around buildings and then to establish turfgrass on the subsurface material that remains (Christians, 2004). The “fill” soil is low in organic matter, lacking nutrients, and high in clay. In this situation, turfgrass managers must go to great lengths to modify and manage the soil.

Soil pH has a unique relationship with the chemical solubility in that it can determine what nutrients will be soluble and available for plant uptake (McBride, 1994). For example, an acidic soil will often contain large amounts of available Al and Mn in the soil solution which can be detrimental to plant health. In such soils, P is often complexed with Al and Fe, making it unavailable for plant uptake. At high pH, soils may have excessive Ca in the soil solution that can also bond to P, making P unavailable. Phosphorus is most available when soil pH is between 5.5 and 7.5. The availability of N is affected by pH because the soil bacteria responsible for mineralization and nitrification of organic N are intolerant of acidic conditions. At a high pH, N can be lost due to volatilization. Therefore, knowing the pH of soil is crucial for plant growth. Having knowledge of the nutrients present and available in the soil for adequate turfgrass growth is critical, as well.

1.5.2 Compaction

Turfgrass soil can become extremely compacted due to frequent use by numerous players. This compaction decreases pore space in the soil and causes poor turfgrass growth and quality. Turf cover is often obliterated by frequent intense games played on soggy soils, leaving an upheaval of soil and turfgrass that need immediate action in order to save the remaining turfgrass coverage in the intensely used area (Adams and Gibbs, 1994). These high intensity use areas are typically down the center of a field and at each end of the field near the goals or goal lines, depending on the sport. For example, on soccer fields approximately 70% of play occurs on 30% of the play area, leading to the characteristic 'diamond' pattern of wear from goal to goal (Adams and Gibbs, 1994). The pattern of turf wear on football and rugby fields is different from soccer fields; the most intense wear in these two sports occurs along the length of the yard lines, particularly those in front of the grandstands (Adams and Gibbs, 1994). Extreme wear takes place in the goal zones that often become devoid of turfgrass, and it is common for the entire center strip of a field to become completely bare by the end of a playing season (Adams Gibbs, 1994).

During a game of soccer, each player will typically travel 10 km and take 12,000 steps (Adams and Gibbs, 1994). Adding up all the players, this is 264,000 steps per game, and this does not include referees, coaches, maintenance workers, or the equipment used to maintain the field. In addition to the compaction caused by the weight of the players on the field, the players' sliding and/or cleats easily tear the turf (Adam and Gibbs, 1994). This sliding and tearing causes an upheaval of turfgrass and clumps, leaving the soil surface exposed. The net effect is the creation of a thin crust at the soil surface that reduces water infiltration, increasing susceptibility to compaction as the season progresses (Adams and Gibbs, 1994). This also means that more nutrients can be lost through surface water runoff, negatively effecting the surrounding environment (Pengthamkeerati et al., 2006).

Soil compaction also affects the availability of plant nutrients. For example, Pengthamkeerati et al. (2006) examined the effect of compaction, and additions of poultry litter, on N mineralization in a clay pan soil. The study found that N mineralization decreased as bulk density increased from 1.2 to 1.8 Mg m^{-3}. This decrease was likely due to destruction of large pores, leading to a decreased water and oxygen supply for soil microorganisms.

1.5.3 Aeration

Aeration plays a large role in soil and plant health. The air-filled porosity of high intensity use areas can be less than 5% by the end of the season for winter sports (Adams and Gibbs, 1994). Aerating the playing field one to two times per year is a common method of reducing soil compaction and increasing porosity. By reducing compaction, aeration allows for deeper and faster penetration of water, air, fertilizer, and chemicals, helps to release "trapped" gases, helps to relieve localized dry spots, controls thatch, increases rooting, and helps reseeding during renovations (Cisar, 1999).

Core aerators and solid-tine aerators are two types of equipment that are used to decrease soil compaction. Core, or hollow tine, aerators are a universally accepted technique in the turfgrass industry for relieving compaction and for thatch control. They can also be used in conjunction with topdressing to allow for the addition of sand and/or organic material (Adams and Gibbs, 1994). The hollow tine method of aeration punches a hole into the soil and extracts a core. The resulting core lies on top of the soil surface and may either remain on the surface of the field to slowly break apart due to player wear and natural environmental factors, or the field can be dragged with chains or a mat. Core aeration reduces thatch and relieves compaction, allowing an increased surface area that permits further air and water exchange and increased water infiltration (Kauffman and Watschke, 2007).

The solid tine aerator punctures a hole into the ground. However, the tines can glaze the walls of the hole, creating an impermeable soil and stifling water and root movement through the soil (Sachs, 2004). The benefit of the solid tine is that no debris remains on the soil surface after aeration, decreasing clean up time and labor costs. Solid tines can be used in place of hollow tines when minimal surface disruption is required (Cisar, 1999). Murphy et al. (1993) compared core and solid tine aeration on a putting green. The study found that core aeration lowered the organic matter fraction of the thatch, but increased soil organic matter. Solid tine aeration provided short-term benefits, but required repeated application to be effective and exhibited potential for development of a hardpan layer. Murphy and Rieke (1990) suggest that solid tine aeration is effective when used in conjunction with core aeration; core aeration should be performed in the fall and spring seasons, while solid tine aeration is applied midseason.

1.5.4 Topdressing

Topdressing is the application of sand, soil, loam, a combination of soil textures plus turfgrass seed, or other material applied to the soil and system (Adams and Gibbs, 1994). Topdressing is usually done immediately after aeration in early spring to restore the levelness of a playing field, to add organic material to the soil, and/or to manage soil texture (Adams and Gibbs, 2004). Topdressing should include materials similar to the current soil texture of the playing field to prevent the formation of layers and to keep costs at a minimum; topdressing can be expensive (Miller and Cisar, 1990). The addition of the particles and/or soil organic material increases cation exchange capacity, water holding capacity, microbial activity, and water and air infiltration.

1.5.6 Turfgrass Nutrients

Nitrogen, P, and K are the primary nutrients used in relatively large quantities by plants. Nitrogen has a major impact on a number of factors involved in turfgrass management, and N fertilization is the highest cost of a turfgrass fertilization program (Carrow et al., 2001). Plants must have adequate N because N effects plant growth, color, and metabolism. Without sufficient N, plants become yellowed, yields and dry matter production decrease, fruits and flowers are smaller, and plants are stunted and spindly. Healthy turfgrass tissue will contain 3 to 5% N on a dry weight basis (Turgeon, 2008). Plant available forms of N include nitrate (NO_3^-), ammonium (NH_4^+), and urea ($(NH_2)_2CO$) which can be taken up by plant roots or absorbed by the shoots. Root uptake is primarily in the form of NH_4^+ or NO_3^- (Carrow et al., 2001). Urea can be taken up in small amounts by roots and hydrolyzed to NH_3 or translocated to shoots for hydrolysis.

Nitrogen undergoes numerous chemical and biological reactions in soils. For example, organic N can be mineralized to NH_4^+-N, NH_4^+-N nitrified to NO_3^- -N, both NH_4^+-N and NO_3^--N immobilized to organic N, NO_3^--N denitrified to N_2 gas, and/or NH_4^+-N volatilized as NH_3 gas. Organic N comprises over 95% of the N found in soil (Brady and Weil, 2000). Nitrate N is the preferred N source for most plants (McCarty et al., 2003). Ammonium usually does not leach because it is a positively charged ion (cation) and is attracted to negative charges in the soil. Nitrification of NH_4^+ to NO_3^- by soil microorganisms is favored by warm soil temperatures, adequate soil moisture, and adequate soil oxygen (McCarty et al., 2003). Nitrification does not readily occur under extreme temperatures, in saturated or poorly aerated soil, in excessively dry soil, or in low pH soil (McCarty et al., 2003). If nitrification does not occur, NH_4^+ may accumulate to a point at which it becomes toxic to plants. Nitrate is readily soluble in water and due to its negative charge, very mobile in soil. It is more likely than NH_4^+ to leach into groundwater and cause environmental and human health problems. Hydrogen ions (H^+) are also produced during nitrification, which will reduce soil pH.

Immobilization converts plant available inorganic N to the unavailable organic form (Brady and Weil, 2000). Soil microorganisms use NH_4^+-N and NO_3^--N when decomposing plant residues, temporarily "tying up" these plant available forms of N. This can be a major concern if residues have a high C:N ratio such as wheat straw, corn stalks, and sawdust. As the C:N ratio narrows, decomposition occurs more rapidly.

Denitrification is the reduction of NO_3^- to gaseous N, either as molecular N or as an oxide of N (Brady and Weil, 2000). When soil does not have sufficient air, microorganisms use NO_3^- as an electron acceptor and rapidly convert NO_3^- to NO and N_2, which escapes to the atmosphere. This transformation can occur within two or three days in poorly aerated soil and can result in large loses of nitrate-based fertilizers (Brady and Weil, 2000).

Volatilization occurs when NH_4^+ ions are transformed into NH_3 gas and lost to the atmosphere (Brady and Weil, 2000). Soils that have a pH greater than 7.5 can lose large amounts of NH_4^+. To minimize these losses, urea and anhydrous ammonia fertilizers are incorporated or injected below the soil surface.

Phosphorus is involved in photosynthesis, respiration, energy storage and transfer, cell division and enlargement, and root growth (Turgeon, 2008). Soil test P levels of 15 to 30 mg P kg^{-1} of soil, and 0.3 to 0.6% P in leaf tissues, are usually considered sufficient (Aldous, 1999). Without P, plants may be purple in color, have delayed maturity and/or lack of flowering, have stunted shoot and root growth, and in grains, reduced tillering. Although large quantities of P may be present in the soil, only very low concentrations are actually in the soil solution and plant available at any given time. In soils, P can readily form insoluble compounds with Fe and Al, rendering the P unavailable to plants (Turgeon, 2008). In most forms, soil P is slowly soluble, resists leaching, and remains in the root zone.

Sources of P include soil minerals, commercial fertilizers, animal manures, plant residues, and waste materials. Like N, soil P exists in organic and inorganic forms. Organic P is found in humus and other organic materials and becomes available through mineralization. Phosphorus is taken up by the plant roots as orthophosphate ($H_2PO_4^-$) (Brady and Weil, 2000). Although leaching of P can occur under certain conditions, the major mechanisms of P loss in agricultural systems are erosion (particulate P) and runoff (dissolved P) (Udawatta et al., 2004).

Potassium is the second most abundant primary nutrient, after N (McCarty et al., 2003). Potassium does not dramatically influence plant growth, but it strongly affects tolerance to drought, cold, high temperatures, wear, and salinity stresses (McCarty et al., 2003). It is essential for protein synthesis and the opening and closing of stomata (McCarty et al., 2003). Plants absorb the ionic form of K (K^+) and may do so in excess, otherwise known as luxury consumption (McCarty et al., 2003). Healthy turfgrass tissue will contain 1 to 3% K by dry weight (Carrow et al., 2001). Deficiency symptoms include interveinal chlorosis, rolling and burning of leaf margins, and necrosis of leaf tips (McCarty et al., 2003). Because K is mobile in plants, deficiency symptoms usually occur first in older leaves.

Calcium, Mg, and S are secondary plant nutrients and are applied less frequently as fertilizers than N, P, and K even though turfgrass contains about as much Ca, Mg, and S on a dry weight basis as P (Carrow et al., 2001). Calcium is essential for plant growth as it strengthens cell walls, enhances cell division, encourages protein synthesis, facilitates carbohydrate synthesis, and promotes root formation and growth (McCarty et al., 2003). It is immobile in plants and remains in the older tissue throughout the growing season. This immobility can result in high levels of Ca in plant tissue (Beard, 1973). The plant available form of Ca is Ca^{2+} (Carrow et al., 2001). Calcium deficiencies appear in areas of new growth; roots are short and stubby, leaves are curled, and leaf margins become necrotic (McCarty et al., 2003). Soils will usually supply enough Ca to turfgrass without fertilization, although the quantity of Ca present varies greatly depending on the soil texture, degree of leaching, and the parent material in which the soil was formed (Carrow et al., 2001).

Magnesium is an extremely important macronutrient. It has a key role in chlorophyll production, improves utilization and mobility of P, increases Fe utilization, and is an activator and component of many plant enzymes (Beard, 1973). Therefore, Mg is essential for the maintenance of green color and growth in turfgrass due to its vital relationship with the chlorophyll molecule (Beard, 1973). Plants use Mg as Mg^{2+} (Beard, 1973). Magnesium is relatively mobile within the plant, therefore deficiency symptoms occur first in older tissues, often as a yellowing along leaf edges, leaving a green arrowhead shape in the center of the leaf. Other symptoms include blotchy red margins and necrosis (McCarty et al., 2003). Deficiencies are most common in acidic, sandy soils with low cation exchange capacity, or soils with extremely high pH (McCarty et al., 2003).

Sulfur (S) is a fundamental part of amino acids, as well as other important organic compounds such as biotin and thiamine (Beard, 1973). Healthy turfgrass tissue contains 0.15 to 0.5% S on a dry weight basis (McCarty et al., 2003). The plant available form of S is sulfate (SO_4^{2-}) (Carrow et al., 2001). Deficiency symptoms are general chlorosis, yellowing of the interveinal areas, and scorched leaf tips (McCarty et al., 2003).

Micronutrients are essential elements needed in small amounts, <100 mg kg^{-1}. These include B (boron), chloride (Cl), Cu, Fe, Mn, molybdenum (Mo), and Zn (McCarty et al., 2003). Most soils supply sufficient micronutrients for turfgrass growth because of the low plant micronutrient requirements (Beard, 1973). However, sandy acidic soils, or strongly leached soils can have micronutrient deficiencies (Beard, 1973). Iron is often added to turfgrass systems in low doses because of its role in chlorophyll production; it will "green" the turfgrass without increasing the yield.

1.5.7 Fertilizing Turfgrass

Without a sound plant nutrition and soil fertility program, turfgrass will not sufficiently respond to other management inputs (Carrow et al., 2001). Soil sampling, in conjunction with leaf tissue tests, are used to determine the need for specific nutrients (Schumann et al., 1998). Soils should be tested at least once per year. A routine soil analysis provides the following information: pH, buffer pH, organic matter content, P, K, Ca, Mg, Mn, B, S, Zn, and aluminum (Al).

1.5.8 Fertilizer Options

Fertilizer products, inorganic or organic, should be selected based on the nutrient requirements of the turfgrass (Schumann et al., 1998). Nitrogen is applied in the largest quantities to turfgrass, which increases the chance of NO_3^- contamination of ground and surface waters through leaching and runoff (Easton and Petrovic, 2004). Nutrients entering a water body, N and P in particular, can accelerate the growth of aquatic weeds (e.g. eutrophication); dissolved oxygen decreases and fish kills increase (Edwards and Daniel, 1994). Correct fertilization practices do not, in general, cause excessive nutrient losses from turfgrass. Gross, et al. (1990) found runoff losses of

NO^-_3-N from turf to be low, specifically <1% of applied fertilizer (Easton and Petrovic, 2004).

Nitrogen fertilizer sources can be separated into three groups: inorganic, natural organic and synthetic organic (Aldous, 1999). Inorganic N fertilizers offer quick release characteristics and high water solubility, providing a rapid plant response that can occur in a few days and last up to a few weeks (Aldous, 1999). Because of their high water solubility, these materials degrade quickly and rely less on microorganisms and temperature to decompose the outer coatings. The most commonly used inorganic N fertilizers for turfgrass are ammonium nitrate, ammonium sulfate, and calcium nitrate (Aldous, 1999).

Organic fertilizers are popular because they offer slow-release characteristics that can sustain dark green turfgrass for relatively long periods of time (i.e. months) and because they add additional micronutrients and organic matter to the soil. Organic fertilizer products typically derive their nutrients from the remains of, or as a by-product of, an organism (Aldous, 1999). Blood meal, fish emulsion, manure, and sewage sludge are examples of organic fertilizers. Because of their low N content (2 to 15%), these products are applied at much higher rates than synthetic inorganic fertilizers.

Johnson et al. (2006) found that topdressing composted organic dairy manure onto established turf improved soil physical properties by lowering bulk density and increasing soil moisture retention. The study also found that NO_3-N concentrations in runoff from organic dairy manure compost treatments were lower than the NO_3-N concentration found in the irrigation water. Angle (1994) reported that the addition of organic amendments reduced soil bulk density and increased water infiltration rates and nutrient holding capacities in turfgrass production.

In addition, organic amendments can enhance turfgrass establishment and quality compared with inorganic sources of nutrients (Gaudreau et al., 2002). Norrie and Gosselin (1996) used paper sludge as an organic amendment on turfgrass and found that the paper sludge mixtures generally increased soil organic matter, although N fertilizer was needed to counteract the high C:N ratio of the sludge. Eghball (2000) found that application of beef cattle feedlot manure reduced N mineralization by 50% compared with non-composted feedlot manure. Lower N availability from compost reflects that the loss of easily convertible N compounds during composting and the presence of stable N compounds. The study also found that N mineralization was similar in the no-till and conventional systems even though manure and compost were surface applied in the no-till plots.

Poultry litter is another organic nutrient source. Organic N comprises the greatest percentage of N in poultry manure, mineralizing over time in response to temperature, moisture, and microorganism activity (Read et al., 2006). Mineralization of organic N from poultry litter occurs rapidly once mixed with soil (Golden et al., 2006). Many agricultural recommendations state that about 50% of the N in organic fertilizers will mineralize during the first year of application (Kuepper et al., 2003; Read et al., 2006; Dinku et al., 2008). Estimates of the percentage of N mineralized in poultry litter range from 40 to 90% (Bitzer and Sims, 1988). Sims (1986) found that the percentages of organic N mineralized in the poultry litter within 150 d were 25 to 40% at 25°C and 17 to 64% at 40°C (Bitzer and Sims, 1988). Castellanos and Pratt (1981) found that approximately 48% of the organic N in poultry manure mineralized within l0 weeks at 23°C. Cabrera et al. (1993) reported that 60 to 77% of organic N from poultry litter was mineralized during a 35d study.

Organic sources can be used in conjunction with synthetic fertilizers. Evers (2002) suggested applying poultry litter in combination with synthetic N fertilizers to achieve maximum yield on forage crops. They reported that when an annual ryegrass (*Lolium multiflorum* L.)'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] pasture system received 9 Mg ha^{-1} poultry litter in the fall (surface applied) in combination with spring applications of synthetic fertilizer (total 168 k N ha^{-1}, increased yield and N, P, and K uptake. They proposed that excess soil P and K derived from poultry litter applications could be reduced through synthetic N fertilization.

Turfgrass clippings that are not removed from a mowed area can act as a slow release fertilizer, as well. Nutrients become available for plant uptake when the organic compounds of the turfgrass tissue decompose. Clippings on a dry weight basis contain 2 to 6% N, 0.10 to 1% P, and 1 to 3% K, as well as other nutrients (Carrow et al., 2001). When recycled back into the sod, clippings may contribute 20 to 35% of annual N needs along with other nutrients contained in the tissues (Carrow et al., 2001). In fine textured soils, N fertilizer needs can be reduced by 10 to 35% after one to two years of returning clippings (Carrow et al., 2001). However, in coarse textured soils such as sands, leaching losses may reduce the effectiveness of this practice (Carrow et al., 2001).

Synthetic organic N fertilizers primarily used on turfgrass sites are urea and urea-based compounds; both quick and slow release forms (Aldous, 1999). Typically, quick release fertilizers are used when frequent light applications are necessary for generating a quick plant response (Schlossberg and Schmidt, 2007). One of the drawbacks of using quick release fertilizers is that, due to their thin coatings and water solubility, they have a higher potential to leach through the soil profile or to runoff into nearby surface waters if applied prior to an intense rain event. Slow release fertilizers are typically used for less frequent, heavier, long lasting applications that provide a constant nutrient supply over a long time period; weeks to months (Bowman, 2003). They are safer to use in regards to salt burn potential because the materials degrade slowly.

Two common sources for P are superphosphate (0-15-0) and triple superphosphate (0-46-0) (Aldous, 1999). Monoammonium phosphate (11-48-0) and ammonium phosphate-sulfate (16-20-0 plus 15% S) are common N fertilizers that are high in P.

Common K fertilizers are muriate of potash (0-0-60) and potassium sulfate (0-0-50-18S) (Aldous, 1999). Often N plus K fertilizers are mixed to ensure that both nutrients are available to the plant.

Commercial sources of Ca include calcitic and dolomitic limestone, gypsum, superphosphates, calcium nitrate, shells, slags, and water treatment residues (McCarty et al., 2003). Magnesium sources include dolomitic limestone, sulfate of potash and magnesium, magnesium sulfate (Epsom salts), and chelates (McCarty et al., 2003). Sulfur sources include gypsum, elemental sulfur, ferrous sulfate, ammonium thiosulfate, potassium magnesium sulfate, sulfur coated urea, and potassium sulfate (McCarty et al., 2003).

1.5.9 Mowing

Proper mowing practices promote rooting, plant density, and uniform growth (Miller and Cisar, 1990). Mowing should remove no more than one-third of the leaf surface area at any one time (Miller and Cisar, 1990). Fine-leaved fescues and bentgrasses can be mowed at heights of approximately 5 mm whereas most cultivars of perennial ryegrass and smooth-stalked meadow grass become stressed if mowed shorter than 20 mm (Adams and Gibbs, 1994). The stress caused by close mowing is primarily a result of removing a high proportion of the actively photosynthesizing leaf tissue (Adams and Gibbs, 1994). It is also important to note that the mower blades should be extremely sharp. Dull blades will leave the stems ragged and they can become chlorotic and prone to disease. A reel mower produces the finest cut because of its scissor-type clipping method (Miller and Cisar, 1990). A striping effect can be achieved by mowing strips (i.e. between each five yard line) the same direction continuously (Miller and Cisar, 1990). Although clippings often are returned to the field to help recycle nutrients, excessive clippings will block sunlight and form a habitat favorable for disease. Large quantities of clippings should be dispersed or removed.

1.5.10 Irrigation

Supplementing natural rainfall with irrigation is necessary to maintain a desirable playing field. Turfgrass is irrigated to ensure water supply from the soil does not delay seed germination or restrict turf growth, to prevent death of drought susceptible species, to maintain a good verdure (greenness), to prevent development of dry patches, and to wash out any accumulated salts (Adams and Gibbs, 1994).

Timing and rate of irrigation are keys to correct irrigation. In warmer climates or during the summer months, it is necessary to irrigate a minimum of one to two times weekly to prevent stress on the turf (Miller and Cisar, 1990). Irrigating more frequently (i.e. daily) with light rates of water can encourage shallow turf rooting and increased pest activity (Miller and Cisar, 1990). It is also extremely important to know the quality of the water being used to irrigate. For example, irrigating with water that has increased levels of salt can make a soil saline which then calls for remediation. In addition, it is imperative that the irrigation system is calibrated in order to determine specific amounts of water being applied. Calibration can be performed by randomly placing several empty cans throughout the field/area to be irrigated and measuring the time required to collect the desired amount (Miller and Cisar, 1990).

Chapter 2

USING PELLETIZED POULTRY LITTER AS A NUTRIENT SOURCE ON ATHLETIC FIELDS

2.1 Introduction

As communities all over the country grow, there is an increased demand for safe athletic fields. A safe athletic field can be defined as a field that has adequate turfgrass coverage and uses a limited amount of chemicals (e.g. insecticides, herbicides, fungicides). Complete turfgrass coverage aids in traction, absorption of shock produced by the athletes, and cushioning to shield athletes from hard falls. To develop and maintain adequate turfgrass coverage, the plant and soil community must be properly managed. Turfgrass that has adequate amounts of soil nutrients (i.e. proper fertilization) recuperates more quickly and can withstand the repeated stresses put upon it. The amount of fertilizer needed varies depending on the species of turfgrass and the area of the country in which the turfgrass is grown, and the soil type in which the turfgrass is grown. Nutrients, especially nitrogen (N), are applied to turfgrass fields in order to keep the fields a healthy green color and to maintain turfgrass that will withstand constant use and recover quickly. Nutrients are not applied to increase growth because this would also increase the mowing frequency and subsequently increasing labor and equipment expenses (Bowman, 2003).

Two commonly available fertilizer source options that are widely used in turfgrass systems are quick release fertilizers and slow release fertilizers. Both quick and slow release fertilizers offer certain pros, cons, and situations in which one is better to use over the other. Typically, quick release fertilizers are used when frequent light applications are necessary generating a quick plant response; they are highly soluble fertilizers that provide nutrients to the plant for a very short time period; over the course of a few days to weeks (Schlossberg and Schmidt, 2007). One of the drawbacks of using quick release fertilizers is that, due to their thin coatings and water solubility, they have the potential to leach through the soil profile or to runoff into near by surface waters if an application is made prior to an intense rain event. In addition, nutrients can easily be lost and the potential for salt damage to the plant is higher. Slow release fertilizers are typically used for less frequent, heavier, long lasting applications that provide a constant nutrient supply over a long time period- weeks to months (Bowman, 2003). They are safer to use in regards to salt burn potential because it takes longer for the material to degrade and become available to the plants. When used properly, slow release fertilizers are more environmentally friendly due to their water insoluble and/or coated nature making the fertilizer less likely to leach downward through the soil profile into groundwater, lessening nutrient losses (Schlossberg and Schmidt, 2007). The turfgrass industry has commonly used slow release fertilizers such as organic materials. However these materials were most popular prior to the 1930's before synthetic urea $[(NH_2)_2CO]$ - based fertilizers were developed (Garling and Boehm, 2001). One of the disadvantages of using slow release fertilizers is that the nutrient contents and release rates can be extremely variable depending on the source, especially animal manures; the advent of synthetic urea offered more consistency and reliability (Garling and Boehm, 2001). Recently, however, there has been a renewed interest in the use of organic materials due to increased public awareness and education in environmental issues such as nutrient pollution to surface waters, drinking water safety, and waste disposal techniques (Garling and Boehm, 2001). This renewed interest has propelled the publics' desire to use more locally available organic fertilizer sources (Garling and Boehm, 2001). Poultry manure is an example of a locally available organic fertilizer.

Delaware is located in the eastern section of the Delmarva Peninsula (Delaware¸ Maryland, and Virginia). The total area of Delaware is 2,396 square miles with a land area of 1,954 square miles, making it the second smallest state in the nation (National Atlas, 2008). Delaware contains three counties- Kent, New Castle, and Sussex. Historically, Kent County and Sussex County have been predominately agriculture. There are approximately 2,546 farms in Delaware and more than half of those farms (54%) are located in Sussex County (USDA, 2008). Most of those farms are either in poultry production, 918 farms, or producing grain crops that aid in the production (feeding) of poultry operations (USDA, 2008). The 2007 Census of Agriculture reported that the state of Delaware sold 246,098,878 chickens ranking 8th in the United States for broilers and other meat type chicken production while Sussex County Delaware ranked number one in the United States (USDA, 2008).

Broiler chickens (*Gallus gallus domesticus*), are typically raised on concrete, wood, or earth floors with a 5 to 15 cm layer of sawdust, peanut hulls, or other bedding material that can be used as an absorptive base (Collins, 1996). The manure and bedding mixture, otherwise known as litter, is removed every one to five years and replaced with fresh bedding material. A standard poultry house will hold up to 25,000 chickens per flock with a new flock replacement approximately five times per year (Paudel and McIntosh, 2005). A typical poultry house will produce approximately 125,000 chickens annually resulting in 134 tonnes of litter material

(Paudel and McIntosh, 2005) which must be either stored, transported, or applied to land (López-Mosquera et al., 2008). Poultry litter can serve as a source of nutrients for plants, supplying approximately 25% to 50% of plant needs (Collins, 1996). Corn (*Zea mays* L.), soybean (*Glycine max* L.), pasture, and horticultural plants are just a few examples of crops that respond well to the application of poultry litter. Poultry litter also contains micronutrients and organic material (López-Mosquera et al., 2008). The total N content of fresh poultry litter is usually three percent or more making it an excellent slow release fertilizer source (López-Mosquera et al., 2008). However, nutrients from poultry litter can be easily lost depending on handling, application, and management techniques. Because poultry litter is produced at a steady rate, land application may not be at a time when the crops need the nutrients. In addition, some farms produce litter in excess of what is needed for plant growth (Paudel and McIntosh, 2005).

Storage and land application of fresh poultry litter can lead to problems including offensive odors, environmental degradation of near by surface waters due to chemical and microbial contamination, and increased N emissions into the atmosphere (López-Mosquera et al., 2008). Continuous land application of poultry litter to agricultural fields- in excess of plant nutrient needs, occurring on a regular basis will increase soil test phosphorus (P) levels (DeLaune et al., 2004). After decades of applying poultry litter to agricultural fields, many soils are now considered excessive. Nutrients such as N and P that are not adsorbed to the soil or used by the plant can move to nearby water bodies causing accelerated aquatic weed growth (e.g. eutrophication) (Paudel and McIntosh, 2005). Alternatives to land application are now being researched due to the environmental consequences of over application of nutrients.

One alternative is to pelletize the poultry litter and use it as a fertilizer source. Perdue® AgriRecycle™ operates such a plant in Seaford, DE. The process of creating the pelletized poultry litter (PPL) begins on the farm. Perdue® AgriRecycle™ (2001) has signed contracts with poultry producers in Delaware and the surrounding area, which allows the company to remove surplus litter from the poultry producers' farms. Once the fresh poultry litter is in the plant it is subject to a variety of processes which include heating, pasteurization, moisture removal, destruction of bacteria and weed seeds, and pelletization. The finished product is stored in an enclosed warehouse until it is shipped by truck or railway (Perdue® AgriRecycle™, 2001).

Perdue® AgriRecycle™ (2006) produces 45,359 tonnes of PPL per year. This product is certified by the Organic Materials Review and marketed as MicroStart60Plus™ fertilizer with a nutrient analysis of 4% N, 2% P, and 3% potassium (K). The product also includes calcium (Ca), magnesium (Mg), and iron (Fe). It is low in salt and free of contaminants (Perdue® AgriRecycle™, 2006). Because the pelletized product is free of pathogens and certified organic, it is safe to apply around people and animals.

Currently, golf course superintendents are using the PPL on their fairways. There has also been an interest in using PPL in urban applications such as lawns, recreational fields, and athletic fields. St. Andrew's School became interested in PPL as an alternative to synthetic fertilizers for their athletic fields. The school felt that an organic fertilizer would be safer for the students using the athletic fields and that it would be a more environmentally friendly fertilizer source.

Athletics at St. Andrew's are greatly valued. Outdoor facilities include five soccer fields, two field hockey fields, practice and game football fields, two baseball diamonds, and four lacrosse fields. The outdoor facilities are used year-round, including during the summer session when a variety of athletic camps and an environmental summer camp are offered to the surrounding community. With such a wide variety of athletic sports each season, the outdoor athletic fields are highly used and intensely managed, year-round.

St. Andrew’s was interested in improving the turf quality on their athletic fields. Two strategies were examined that may result in such improvements; the use of PPL as a fertilizer and the use of two different types of aerators. To evaluate these practices, this project compared existing fertilizer applications with PPL and compared a vibrating solid tine aerator with a core aerator. The goal of this project was to evaluate soil and turf nutrient concentrations, as well as turf quality, when PPL was used as a fertilizer on athletic fields.

Typically, turf quality is measured visually by examining turfgrass color, uniformity, and density of the stand. Unfortunately, visual assessments are subjective, susceptible to inconsistencies, time consuming, and have the potential to be expensive (Bell et al., 2002). A relatively new option to determine turf quality is to use multispectral radiometry as a means of determining turfgrass biomass (Bell et al., 2002). Multispectral radiometry measures the reflectance of turfgrass in the visible and near infrared portion of the electromagnetic spectrum. Healthy turfgrass tissue will contain a large amount of chlorophyll, which absorbs red (R) and green (GRN) radiation and reflects near infrared radiation (NIR). A plant in poor health contains less chlorophyll than a healthy plant. Less chlorophyll in a plant increases the amount of R and GRN radiation that is reflected while decreasing the amount of NIR reflection because more NIR is absorbed by the plant (Bell et al., 2002). Due to the inverse relationship of the visible and the NIR, vegetation indices may be created to determine the amount of biomass in a plot (e.g. NIR/GRN).

2.2 Materials and Methods

A 2.5-year study was performed on three active athletic fields at St. Andrew's School, located in Middletown, Delaware: a football field, football practice field, and a soccer field. The soil was a Sassafras sandy loam (fine-loamy, mixed, mesic, Typic Hapludult) (USDA, 1970). Turfgrass on the athletic fields was a blend of perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea*). The climate is humid and continental due to the site's proximity to the Atlantic Ocean and Chesapeake Bay. Total calendar year precipitation in 2007 was 106.2 cm at the New Castle County Airport 36.19 km from St. Andrew's School (DE Geological Survey, 2008).

The study was designed as a stratified complete block with four treatments, three blocks, and five replications (one field had four replications). The four treatments included vibrating aeration and synthetic fertilizer (VS), core aeration and synthetic fertilizer (CS), core aeration and pelletized poultry litter (CP), and vibrating aeration and pelletized poultry litter (VP). The blocks were placed to capture the effects of different use intensity (low; sidelines, moderate; field edge, and heavy; field center). Study designs for each field are shown in Figures 2.1, 2.2, and 2.3.

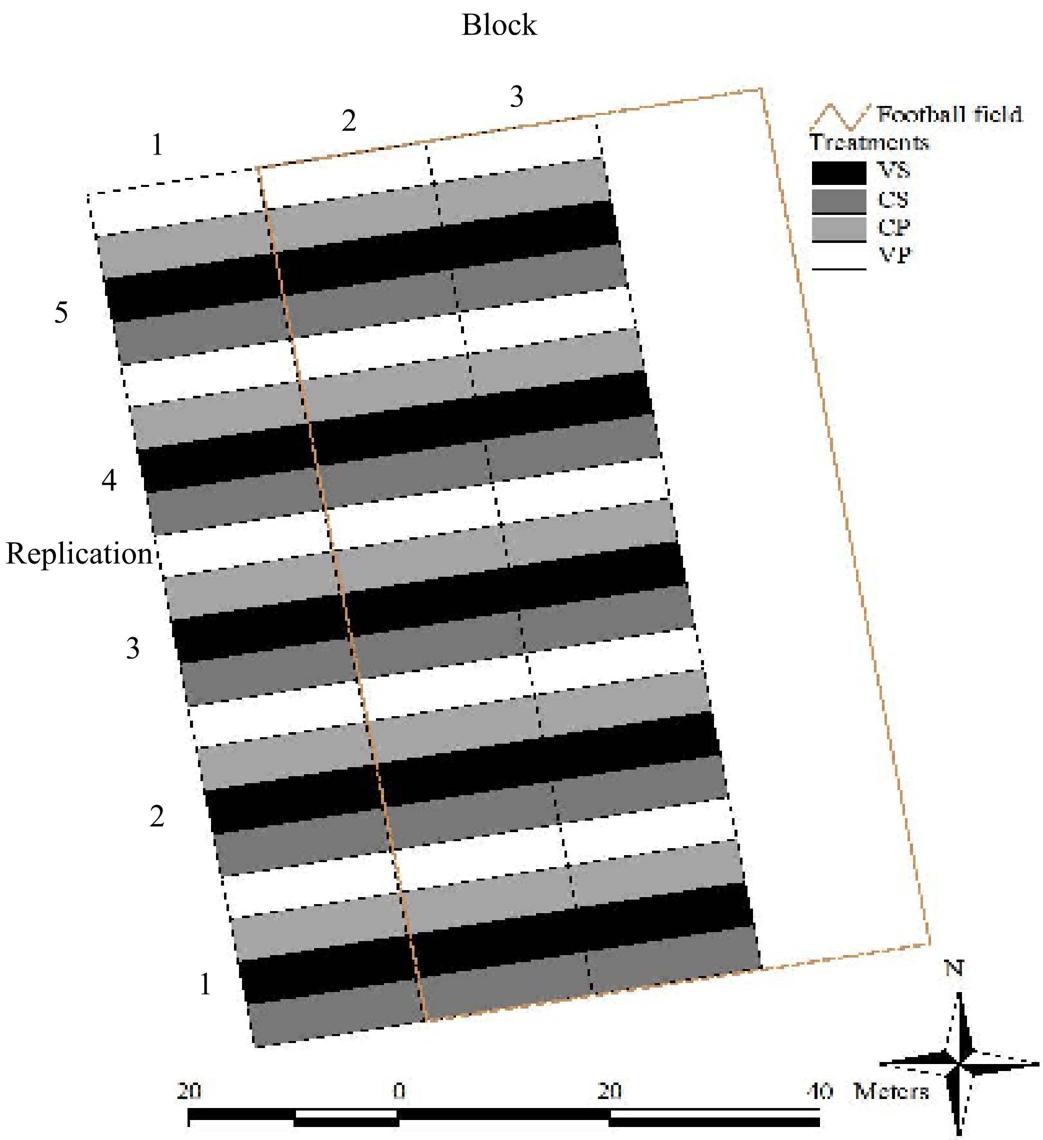

Figure 2.1. Treatments applied to the football field at St. Andrew's School where VS is synthetic fertilizer with vibrating aeration, SC is synthetic fertilizer with core aeration, CP is pelletized poultry litter with core aeration, and VP is pelletized poultry litter with vibrating aeration.

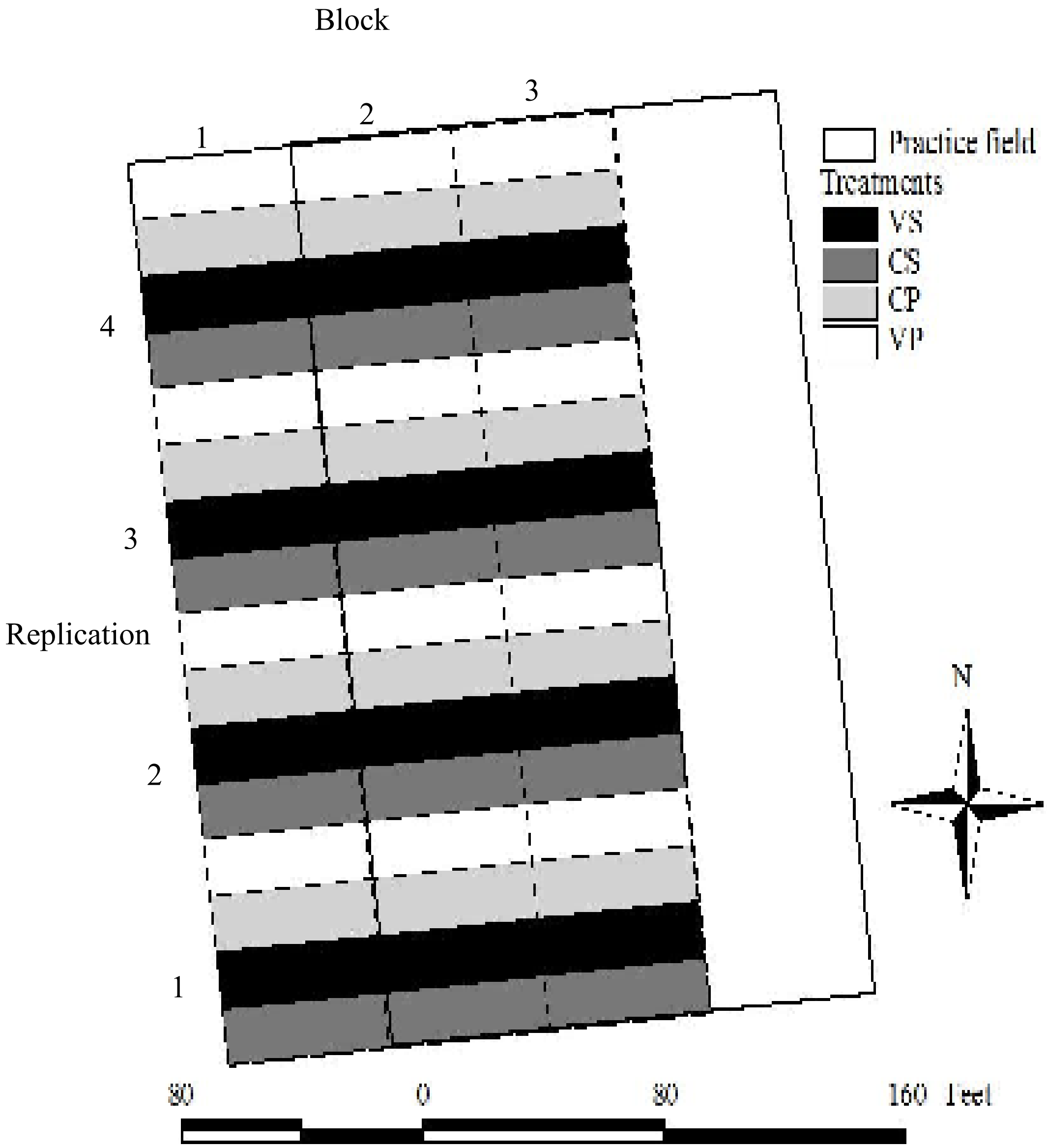

Figure 2.2. Treatments applied to the practice football field at St. Andrew's School where VS is synthetic fertilizer with vibrating aeration, CS is synthetic fertilizer with core aeration, CP is pelletized poultry litter with core aeration, and VP is pelletized poultry litter with vibrating aeration.

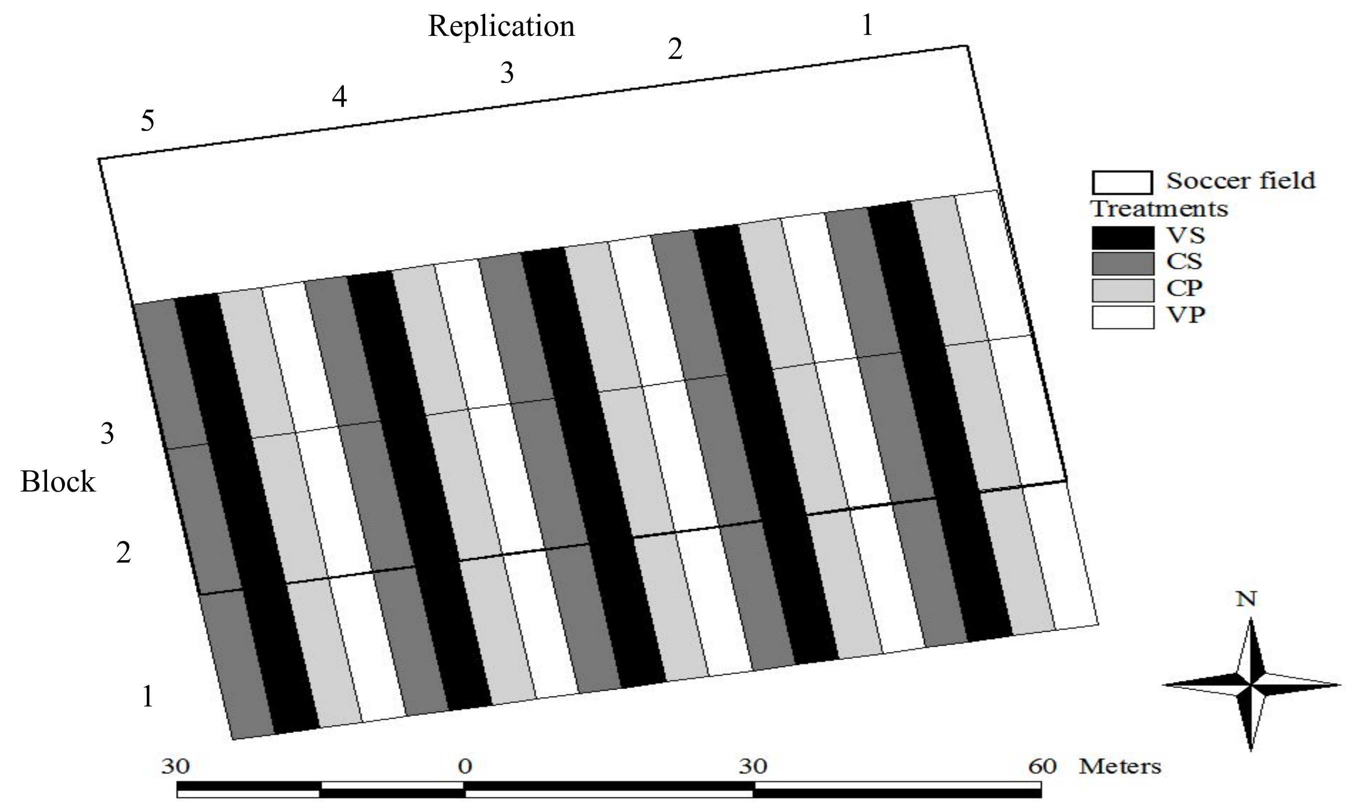

Figure 2.3. Treatments applied to the soccer field at St. Andrew's School where VS is synthetic fertilizer with vibrating aeration, CS is synthetic fertilizer with core aeration, CP is pelletized poultry litter with core aeration, and VP is pelletized poultry litter with vibrating aeration.

Standard turfgrass management at St. Andrew's is fertilization twice per year with synthetic fertilizers and aeration once per year using a core aerator, therefore this treatment (CS) serves as the control, or reference. Rates of fertilization and timing of aeration were determined by St. Andrew's School. Aeration was performed per industry standard recommendations immediately after the last game of the football season so as not to interfere with play (Bruneau et al., 2001).

Treatments were applied to 5m-wide strips across the width of each field and included an area adjacent to the field. Five replications were used on the football field and soccer field, and four replications were used on the practice football field due to its shorter length.

Plots were aerated on November 27, 2006 and November 20, 2007 prior to sampling and fertilization. Core aeration was performed with a Ryan Tracaire® Aerator with 15 cm tines spaced 21.6 cm apart. Each core was 2.54 cm in diameter. This piece of equipment had a 1.8 m aerating width, ten tines per wheel with eight wheels in total. Vibrating aeration was performed with an Aera-vator® Aerator with 3.8 cm tines. The tines create holes 3.8 cm in diameter. This piece of equipment had a 203 cm, or 2 m, aerating width with eight wheels, each having 14 tines. Fertilizer treatments were applied after aeration in the fall of 2006 and 2007, and in the spring of 2007 and 2008. The fall fertilization took place on December 5, 2006 and November 28, 2007. A synthetic fertilizer, 6-16-34, was applied to the VS and CS plots at 224 kg ha^{-1} (13 kg N ha^{-1}). The PPL (4-2-3) was applied at a rate of 673 kg ha^{-1} (26 kg N ha^{-1}, or 13 kg ha^{-1} of available N).

The PPL used for this study was from the Perdue AgriRecycle Pelletizing Plant in Seaford, DE. The product is a certified organic fertilizer derived from poultry litter. Total N content of the PPL is 4%, of which 0.4% is ammoniacal N, 1.6% is water soluble N, 2.0% water insoluble N, and 2% slowly available N. Plant-available N from the PPL was calculated as 50% of total N applied (Kuepper et al., 2003). Phosphorus content (P_2O_5) of the PPL is 2%, and K content (K_2O) is 3%. The PPL also contains 2% Ca, and 0.5% Mg.

The spring fertilization took place on April 24, 2007 and April 9, 2008. Synthetic fertilizer (32-3-4 Premium Early Spring Lawn Food with Crabgrass Control) was applied at a rate of 122 kg ha^{-1} to the VS and CS plots (39 kg N ha^{-1}). This fertilizer was 1.17% ammoniacal N and 30.83% urea N; 5.76% of the urea N is slowly-available N from polymer-coated and sulfur-coated urea. Both P and K were considered completely available. The fertilizer also contained 5% sulfur (S) and 1% Fe. The PPL (4-3-2) was applied at a rate of 1952 kg ha^{-1} to the VP and CP plots (78 kg N ha^{-1} or 39 kg ha^{-1} of available N)

Due to the Crabgrass control being included in the synthetic fertilizer application, a Crabgrass control (Dimension®) was included with the PPL treatments at a rate of 195 kg ha^{-1}.

A Valmar Airflow 1255PF Granular Applicator, with 5 m booms and 12 drops, was used for all applications of synthetic fertilizer, and PPL except during the spring of 2007 when a drop spreader modified with chicken wire was used because the particle size of the PPL product was finer than at other times.

Soil samples were collected within one week prior to each fertilization event as well as at the completion of the study on June 9, 2008. Eight soil cores (0 to 10 cm in depth) were collected from each plot with a 3.8 cm diameter soil probe and placed into a clean bucket. The cores were thoroughly mixed in the bucket and then placed into a properly labeled brown paper bag until analyses. Samples from each plot were air-dried, ground to pass through a 2-mm sieve, and analyzed for the following chemical and physical properties by the University of Delaware Soil Testing Laboratory: pH (1:1 water/soil ratio), buffer pH (Adams-Evans), organic matter (by loss on ignition), and Mehlich III extractable nutrients (P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, and S) after Mehlich (1984). The Mehlich III extracts were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Soil resistance was measured with a penetrometer to determine surface compaction (0 to 10 cm) on the athletic fields on November 17, 2006, prior to treatments being applied. The average of four penetrometer measurements per block-replication was used to determine soil mechanical resistance.

Turfgrass clippings (i.e. tissue samples) were collected during each soil sampling event and at the completion of the study on June 9, 2008. The tissue samples, a minimum of 227g of moist grass clippings, were collected from each plot using a manual reel mower and placed in individual brown paper bags. The mower basket was cleaned between plots. The tissue was taken to the University of Delaware, stored in cold storage if necessary, and shipped to Brookside Laboratories for nutrient analyses. All clippings were dried and then ground to pass a 0.5 mm sieve and analyzed for nutrients by Brookside Laboratories, New Knoxville, OH. The following nutrients were determined: N, P, K, Ca, Mg, S, B, Mn, Cu, and Zn. The N content was determined through combustion analysis with a Carlo Erba 1500 series nitrogen analyzer (Gavlak et al., 1994). The samples were digested in a MARS Express microwave with nitric acid and hydrogen peroxide; the digested solution was then run on an inductively coupled plasma atomic emission spectroscope (ICP-AES) for mineral determination (Gavlak et al., 1994).

Spectral reflectance of the turfgrass canopy was collected over the wavelength range 460 to 810nm at eight specific wavebands (center wavelength of 460, 510, 560, 610, 660, 710, 770, and 810nm) using a commercially available multispectral radiometer MSR87 (CROPSCAN, 2005). The MSR87 model consisted of a DLC or A/D converter, terminal, telescoping support pole, connecting cables and operating software (CROPSCAN, 2005). Incident and reflected radiation were measured by orienting the radiometer housing over the diameter of field of view equal to one-half of the height of the radiometer above the turfgrass plot (approximately 1.5m^2). The data acquisition program recorded the percent reflectance for each of the eight wavelengths at each scan as well as ancillary data (e.g. plot number, time, level of incident radiation and temperature). Four scans were collected in each of the 168 plots before disturbance by fertilization, aeration, soil, and tissue collection on November 17, 2006, April 13, 2007, March 27, 2008, and at the completion of the study on June 8, 2008. Leaves and extraneous debris were removed from the plots prior to data collection. Multispectral readings were collected only when the sky was clear/cloud free between the hours of 10:00am and 2:00pm.

Once the readings were obtained, the equipment was returned to the University of Delaware Elbert N. & Ann V. Carvel Research & Education Center in Georgetown, Delaware to be downloaded on to a compatible computer. Turfgrass quality was estimated using a simple band ratio, (NIR/GRN), where NIR (810nm) indicates near infrared reflectance, which estimates biomass, and GRN (560nm) indicates green reflectance values, which estimates depth of green color. Because spectral reflectance of the turfgrass canopy was recorded at different times of the year, and green color is expected to vary during the year, relative values between 0 and 1 were created by assigning the largest NIR/GRN value (highest turfgrass quality) at each sampling time a value of 1 and transforming the other index values accordingly.

This study was conducted on active athletic fields and all turfgrass management practices, other than fertilization, were performed using St. Andrew's normal practices. These include regular mowing, use of fungicides and herbicides, irrigation, and over-seeding with perennial ryegrass. The athletic fields were mowed two to three times per week during the growing season at a 5 cm mowing height with a Bush Hog® model TD 1500. During summer months, the fields were irrigated once per week, or as needed, using a water wheel, Kifco® Model T200. The fields were over-seeded two to three times per year, or when necessary (i.e. to fill in bare spots) using a Jacobsen® drop seeder model 32548.

All statistical analyses were performed using standard procedures of SAS Version 8.0 (SAS Institute, 1998). Analysis of variance for all treatment comparisons and contrast statements was performed using the General Linear Model (GLM) procedure using Type I sums of squares. The model contained the following classes: FIELD, PENETROMETER_CATEGORY, and TREATMENT. The model statement was Y= FIELD|PENETROMETER_CATEGORY|JULIAN_DATE|TREATMENT, where "|" indicates all possible interactions for connected main effects. An alpha of 0.05 was used for all statistical comparisons. Initial samples (i.e. fall 2006) were collected before treatments were applied and a composite was taken for each block-replication. All independent variables were adjusted relative to initial values. For example, a soil P value at the second sampling time was divided by the initial soil P value for that block-replication.

2.3 Results and Discussion

2.3.1 Penetrometer Data

Fields were initially divided into three blocks based on expected intensity of use (low, moderate, and heavy). However, initial soil penetrometer data indicated that blocks did not correlate to intensity of use as expected. Therefore, initial penetrometer data were used to separate areas of the fields into three approximately equal categories. Areas with the highest penetrometer readings (>25psi) became penetrometer category 3 (high use), middle readings (21-25psi) became penetrometer category 2 (medium use), and the lowest readings (<21psi) became penetrometer category 1 (low use) (Table 2.1).

Penetrometer values were integer numbers and therefore difficult to allocate to three equally sized categories. Fifty-three percent of the penetrometer observations in the football field fell into category 3, the high level of use category, while only 20% of the penetrometer observations in the football field fell into category 1, the low level of use category. In contrast, the practice field had 67% of its penetrometer observations in category 1 with zero observations in category 3.

Table 2.1. Frequency of penetrometer observations in three categories for the football, practice, and soccer fields.

Field	Penetrometer Category			Total
	1 (<21psi)	2 (21-25psi)	3 (>25psi)	
Football	3	4	8	15
Practice	8	4	0	12
Soccer	6	7	2	15
Total	17	15	10	42

2.3.2 Soil Nutrients

Initial soil sample results are presented in Table 2.2. Soil pH was 6.1; the target pH value for intensively managed turfgrass is 6.5 (Sims and Gartley, 1996). Initial organic matter was optimum, 2.8%, for the coastal plain soils (Davey, 1984). Soil test values for P were medium while K, Ca, Mg, Zn, Cu, B, and S were in the optimal range for turf; Mn was above optimum (Sims and Gartley, 1996).

There was a difference between fields for all soil parameters (Table 2.3). These differences are probably due to management and use of the fields. For example, the soccer field was modified approximately five years ago by topdressing mushroom compost and sand. Therefore, the football field and the practice field have slightly different textures than the soccer field; the soccer field has a higher percentage of sand. These differences in soil parameters between the fields support the use of field as a class variable in the GLM model.

Soil parameters differed among soil compaction categories, except for organic matter (OM), Mg, Zn, and Cu. In general, the nutrient values were higher in

Table 2.2. Means for initial soil parameters.

Soil Parameters	Mean Soil Parameters Initial
pH	6.1
Buffer pH	7.7
	--------%--------
Organic Matter	2.8
	----mg kg^{-1}----
P	47.8
K	145.1
Ca	981.7
Mg	120.9
Mn	95.2
Zn	2.4
Cu	1.0
Fe	339.8
B	1.5
S	13.7
Al	753.7
PSAT†	15.4

†PSAT, phosphorus saturation ratio

Table 2.3. Model components significance for soil parameters where PC is penetrometer category, JT is Julian time, and TRT is treatment.

Parameter	Model Component							
	FIELD	PC	FIELD x PC	JT	JT x FIELD	JT x PC	JT x FIELD x PC	TRT
	p Values							
pH	0.00	0.00	0.00	0.00	0.00	0.32	0.63	0.25
Buffer pH	0.00	0.00	0.51	0.00	0.03	0.17	0.99	0.48
OM	0.02	0.32	0.01	0.12	0.00	0.05	0.05	0.55
P	0.00	0.00	0.10	0.02	0.75	0.05	0.12	0.19
K	0.00	0.00	0.00	0.00	0.22	0.35	0.02	0.45
Ca	0.00	0.00	0.00	0.00	0.01	0.43	0.00	0.60
Mg	0.00	0.22	0.00	0.00	0.56	0.97	0.08	0.12
Mn	0.00	0.00	0.00	0.00	0.08	0.53	0.58	0.19
Fe	0.00	0.00	0.00	0.00	0.93	0.79	0.45	0.59
B	0.00	0.00	0.00	0.00	0.00	0.49	0.02	0.58
S	0.00	0.00	0.00	0.07	0.00	0.50	0.00	0.80
Zn	0.00	0.94	0.00	0.09	0.15	0.48	0.03	0.13
Cu	0.00	0.18	0.00	0.00	0.11	0.31	0.17	0.57
Al	0.00	0.01	0.00	0.00	0.26	0.53	0.81	0.22
PSAT†	0.00	0.01	0.00	0.00	0.01	0.17	0.30	0.08

†PSAT, phosphorus saturation ratio

the high compaction areas (data not shown). Compaction restricts root growth and nutrient movement in the soil (Roseberg and McCoy, 1992). Restricted nutrient movement will affect the ability of plants to take up nutrients (Taylor and Gardner, 1960; Unger and Kaspar, 1994), which may result in different levels of nutrients remaining in soils that are compacted to different extents. These differences in soil parameters between penetrometer categories (compaction levels) support the use of compaction levels as a class variable in the GLM model.

Soil parameters were affected by compaction differently from field to field, except for buffer pH and P. For each of these nutrients there was no clear pattern, such as an increasing nutrient concentration with decreasing compaction.

All of the soil parameters changed over time, except for OM, S, and Zn. Turfgrass growth is affected by season (temperature, sunlight, moisture, etc.). For example, cold season turfgrass naturally peaks in shoot growth during the spring and goes dormant in the winter, with slightly lower growth in the fall (Carrow et al., 2001; Mangiafico and Guillard, 2006). Therefore, differences attributed to time were expected, but not relevant to the study.

Soil organic matter did not significantly change over time. Ding et al. (2002) suggested that it takes at least ten years of tillage before soil organic matter will significantly change. Therefore, the lack of change in OM over time may be due to the brevity of the study.

The change in soil parameter concentrations over time differed among the three fields for approximately one-half of the soil parameters. Soil P, K, Mg, Mn, Fe, Zn, Cu, and Al did not show a different change over time between fields. These significant interactions were independent of treatments and were likely due to factors related to time and field, as discussed above.

Soil OM and P were the only soil parameters that changed over time among levels of compaction, suggesting that compaction affects the quantity of soil OM and P, and available P for plant uptake. There was a three-way interaction between field, compaction level, and time for the following soil parameters: K, Ca, B, S, and Zn. Such interactions are difficult to interpret and beyond the scope of this study.

After accounting for variation due to fields, compaction, time of sampling, and their interactions, there were no significant treatment effects in measured soil parameters. This lack of treatment effects was expected because soil nutrients were applied at nearly equivalent rates in the fertilizer and PPL treatments. Since aeration method does not affect soil nutrients directly, an aeration effect would be expected only if a significant change in turfgrass biomass occurred.

2.3.3 Tissue Nutrients

Initial tissue concentrations (Table 2.4) indicate that all tissue nutrients were in the optimal range, or higher, for adequate plant growth. Phosphorus and Fe levels were higher than optimal (P was 0.5%; optimum range for tissue P is 0.1 to 0.4% according to Sims and Gartley, 1996). Average Fe levels were 385.3 mg kg^{-1} (optimum range is 20 to 250 mg kg^{-1} according to Sims and Gartley, 1996). Copper concentrations were only slightly lower (4.7 mg kg^{-1}) than the recommended range of 5 to 20 mg kg^{-1} (Sims and Gartley, 1996). Initial tissue B concentrations were low at 2.5 kg mg^{-1}; 6 to 18 mg kg^{-1} is the optimum range for monocots (Sims and Gartley, 1996).

Table 2.4. Means for initial tissue parameters.

Nutrients	Mean Tissue Parameters Initial
	----------%----------
N	4.8
P	0.5
K	2.8
Ca	0.4
Mg	0.2
S	0.4
	-------mg kg^{-1}-------
B	2.5
Fe	385.3
Mn	57.4
Cu	4.7
Zn	24.7
Al	428.5

The statistical model used to analyze tissue nutrients was the same model used for the soil parameters; model component p-values are shown in Table 2.5. There was a difference between fields for all tissue nutrients. This is probably due to the different levels of use among the fields and the higher sand content in the soccer field.

Tissue nutrient concentration differed among soil compaction categories, except for N, Fe, and Al. The lack of difference in N concentration suggests that the degree of compaction was not enough to affect mineralization or denitrification. Typically, soils that are highly compacted will have reduced availability of N, which results in lower plant N concentrations and uptake (Lipiec and Stępniewski, 1995). Iron and Al are needed in very small amounts by turfgrass; therefore these results are not unexpected.

Some tissue nutrients (P, Mg, Mn, B, S, Zn, and Cu) were affected by compaction differently from field to field. For each of these nutrients there was no clear pattern, such as an increasing nutrient concentration with decreasing compaction.

All tissue nutrient concentrations changed over time. The sampling times were fall 2006, spring 2007, fall 2007, spring 2008, and summer 2008. Because the last sampling date was in summer, higher concentrations of tissue nutrients were expected. This resulted in an increasing linear trend in tissue nutrient concentrations. The change in tissue nutrient concentrations over time differed among the three fields for all nutrients, except K and B. There was no clear pattern in the change over time among the fields. There was no three-way interaction between field, compaction level, and time for any tissue nutrients except Zn. Interpretation of this result is complicated; there was no clear pattern present.

Table 2.5. Model components significance for tissue nutrient concentrations where PC is penetrometer category, JT is Julian time, and TRT is treatment.

Nutrient	Model Components														
	FIELD	PC	FIELD x PC	JT	JT x FIELD	JT x PC	JT x Field x PC	TRT	FIELD x TRT	PC x TRT	FIELD x PC x TRT	JT x TRT	JT x FIELD x TRT	JT x PC x TRT	JT x FIELD PC x TRT
	p Values														
N	0.00	0.17	0.83	0.00	0.03	0.86	0.76	0.49	0.85	1.00	1.00	0.95	1.00	1.00	1.00
P	0.00	0.00	0.00	0.00	0.00	0.65	0.27	0.98	0.67	0.99	0.96	0.65	1.00	1.00	1.00
K	0.00	0.00	0.83	0.00	0.17	0.18	0.42	0.93	0.86	1.00	0.82	0.18	0.99	1.00	1.00
Ca	0.00	0.00	0.43	0.00	0.04	0.22	0.31	0.66	0.32	0.74	0.88	0.80	0.63	0.98	0.99
Mg	0.00	0.00	0.01	0.00	0.00	0.30	0.45	0.27	0.64	0.97	0.88	0.91	0.93	1.00	0.97
S	0.00	0.01	0.00	0.00	0.00	0.53	0.64	0.51	0.97	1.00	1.00	0.99	1.00	1.00	1.00
Fe	0.00	0.55	0.89	0.00	0.00	0.26	0.86	0.99	0.98	0.99	1.00	0.87	0.98	0.99	1.00
Mn	0.01	0.00	0.02	0.00	0.01	0.22	0.60	0.01	0.97	0.87	1.00	0.70	0.98	1.00	1.00
Cu	0.00	0.00	0.00	0.00	0.00	0.59	0.06	0.08	1.00	1.00	1.00	0.96	1.00	1.00	1.00
Zn	0.00	0.00	0.04	0.00	0.00	0.86	0.01	0.62	0.89	0.65	0.35	0.05	0.45	0.62	0.21
Al	0.00	0.78	0.44	0.00	0.00	0.20	0.88	0.98	1.00	0.98	1.00	0.85	0.98	0.99	0.99
B	0.00	0.00	0.00	0.00	0.70	0.93	0.11	0.98	0.99	1.00	1.00	0.99	0.98	1.00	1.00

Manganese was the only tissue nutrient whose concentration differed among treatments. Compared to initial concentrations, plots receiving the VS treatment showed an increased in Mn. The increase in Mn was minimal (from 57.4 mg kg^{-1} to a high of 95.8 mg kg^{-1}; optimum range is 20 to 500 mg kg^{-1}) and should not have effected plant growth. Plots receiving the VP treatment resulted in the lowest Mn concentration (83.7 mg kg^{-1}). Neither form of fertilizer contains Mn, and soil Mn concentrations decreased over time, though this decrease was not significant treatments. Perhaps turfgrass in plots receiving VS treatment were better able to extract soil Mn.

2.3.4 Remote Sensing Data

Turfgrass quality, as defined in this study, is the ratio of biomass to depth of green color. Model component p-values can be found in Table 2.6. Based on remote sensing, turfgrass quality was highest in the PPL treatments relative to the standard practice (CS) (Figure 2.1). The CP and VS treatments were not significantly different from one another and produced the largest NIR/GRN values over the course of the study. These results have implications for management. If synthetic fertilizer is used, vibrating aeration appears to result in greater turfgrass quality. If PPL is used, core aeration is optimal.

Level of compaction appears to affect fertilizer efficiency (Figure 2.2). When vibrating aeration is used, compaction does not affect turf quality. When core aeration is used, synthetic fertilizers produce lower turfgrass quality on high compaction areas and PPL results in higher turfgrass quality on low compaction areas.

Table 2.6. Model components significance for NIR/GRN values where PC is penetrometer category, JT is Julian time, and TRT is treatment.

Model Components	NIR/GRN
	------p values------
FIELD	0.29
PC	0.29
FIELD x PC	0.16
JT	0.68
JT x FIELD	0.12
JT x PC	0.94
JT x FIELD x PC	0.05
TRT	0.00
FIELD x TRT	0.00
PC x TRT	0.03
FIELD x PC x TRT	0.00
JT x TRT	0.00
JT x FIELD x TRT	0.00
JT x PC x TRT	0.90
JT x FIELD x PC x TRT	0.03

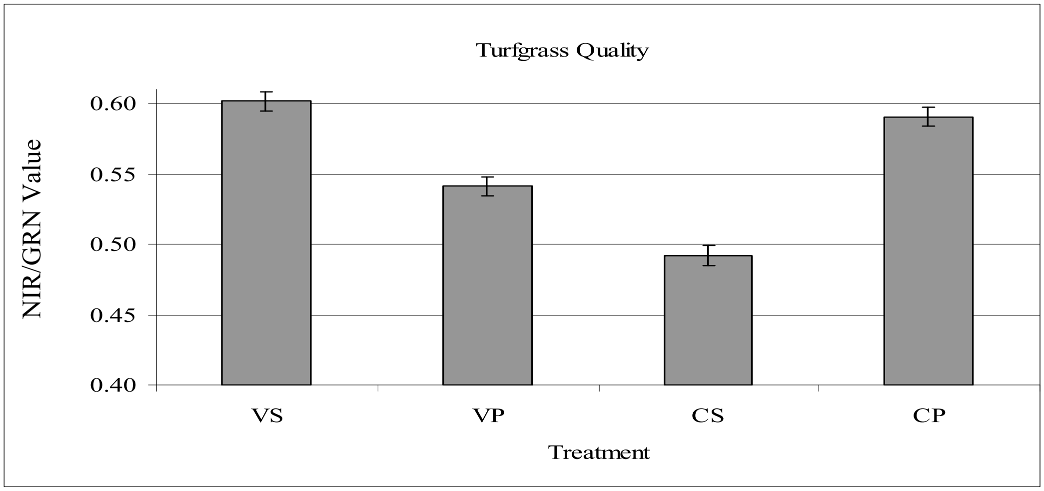

Figure 2.1. NIR/GRN values for each of the following treatments: (VS) synthetic fertilizer with vibrating aeration, (VP) pelletized poultry litter with vibrating aeration, (CS) synthetic fertilizer with core aeration, and (CP) pelletized poultry litter with core aeration. Error bars are LSD at alpha=0.05.

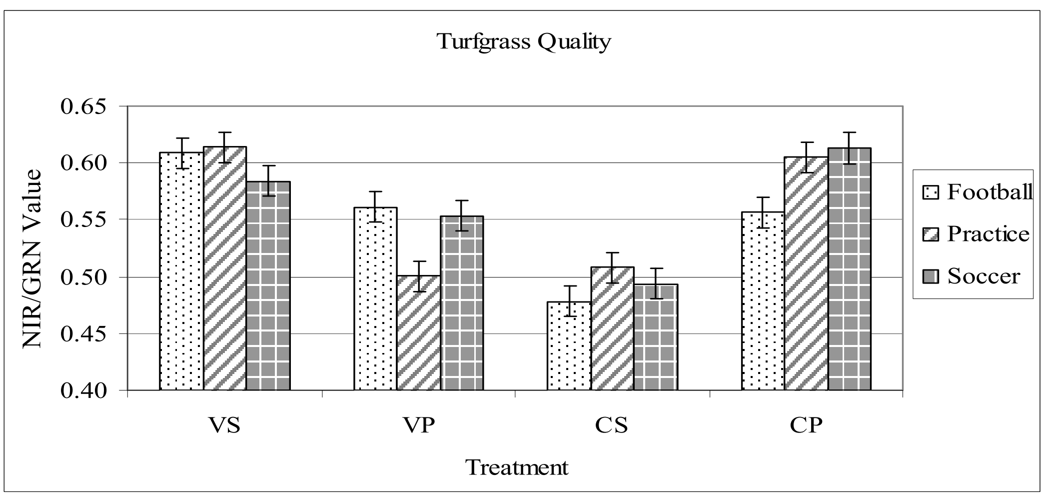

Figure 2.2. NIR/GRN values for each of the following treatments by penetrometer category: (VS) synthetic fertilizer with vibrating aeration, (VP) pelletized poultry litter with vibrating aeration, (CS) synthetic fertilizer with core aeration, and (CP) pelletized poultry litter with core aeration. Error bars are LSD at alpha=0.05.

2.4 Summary and Conclusions

Treatments did not produce significant differences in measured soil and tissue parameters, with the exception of tissue Mn concentration. This indicates that the PPL treatments duplicated the synthetic fertilization effects. However, remote sensing of turfgrass quality revealed significant treatment effects. Lowest turfgrass quality was produced by the current management practice (CS) at St. Andrew's School; to apply synthetic fertilizer in conjunction with core aeration. This suggests that athletic field management at St. Andrew's School could be improved either by use of vibrating aeration, or use of PPL as a nutrient source.

Chapter 3

NITROGEN AVAILABILITY FROM PELLETIZED POULTRY LITTER

3.1 Introduction

Land application of poultry litter provides essential plant nutrients as well as micronutrients and soil organic material (Read et al., 2006). Poultry litter, which is a combination of bedding material and chicken manure, is typically applied at rates based on crop yield goals (Bitzer and Sims, 1988). Traditionally, poultry litter applications have been based on crop nitrogen (N) requirements without regard to phosphorus (P) content (Golden et al., 2006). Often the poultry litter is used on fields that have received annual poultry litter applications for long periods of time. After decades of poultry litter applications, soil test P values have increased well beyond optimum levels for plant growth and have now become excessive (Sharpley et al., 1994).

Large land applications of poultry litter can cause losses of nutrients, particularly NO_3-N to groundwater through leaching and N and P to nearby surface waters through runoff (Preusch et al., 2002). Nutrient-enriched surface water bodies accelerate eutrophication, aquatic weed growth and decreased oxygen levels that suffocate aquatic life forms (Sistani et al., 2008).

The low nutrient, and high moisture, content of fresh poultry litter make transportation costs high. Pelletized poultry litter (PPL) is virtually free of moisture and therefore lighter in weight, resulting in lower transportation costs (Cabrera et al., 1994). PPL is also free of odors and pathogens, making the transportation, storage, and application of the litter much easier (Preusch et al., 2002).

Poultry litter contains both organic and inorganic forms of N (Qafoku et al., 2001). Inorganic N, mostly ammonium (NH_4^+) and nitrate (NO_3^-), is readily available to plants. Organic N comprises the largest portion of the N in poultry litter (Bitzer and Sims, 1988). Before organic N can become plant available, it must first be mineralized to inorganic forms by soil microbes. The rate at which this mineralization occurs is an important factor in determining PPL's plant available N (PAN) levels.

Mineralization occurs in response to a number of factors, predominately temperature, moisture, and microorganism activity (Read et al., 2006). Mineralization of organic N from poultry litter occurs rapidly once mixed with soil (Golden et al., 2006). Many agricultural recommendations state that about 50% of the N in organic fertilizers will mineralize during the first year of application (Kuepper et al., 2003; Read et al., 2006; Endale et al., 2008). However, N mineralization rates of poultry litter are extremely variable, ranging from 21% to 100% (Preusch et al., 2002). For example, Preusch et al. (2002) found that N mineralization rates vary from 42% in composted poultry litter to 64% in fresh poultry litter. When comparing N transformations in poultry litter of varying size (pellet and fine particle) Cabrera et al. (1993) found that 60 to 77% of the organic portion of poultry litter was mineralized over the course of the 35d study. Sims (1986) found that the percentage of organic N mineralized in poultry litter within 150d ranged from 25 to 40% at 25°C and 17 to 64% at 40°C (Bitzer and Sims, 1988). Castellanos and Pratt (1981) found that approximately 48% of the organic N in poultry manure mineralized within l0 weeks at 23°C (Bitzer and Sims, 1988).

Knowing the mineralization rate of PPL could increase monetary savings by improving the predictability of nutrient availability (Griffin and Honeycutt, 2000). The objective of this research was to quantify the PAN from PPL that was mixed or not-mixed into the soil and applied at various N rates.

3.2 Materials and Methods

The laboratory incubation study had a completely randomized design with a total of 240 samples; ten sampling times, eight treatments, and three replications. Treatments consisted of four rates of PPL; both incorporated (mixed) or topdressed (not-mixed). The PPL was applied at rates of 0, 48, 146, and 244 kg N ha^{-1} and either mixed into the soil or not-mixed.

The soil used in this study was a Matapeake silt loam (fine-silty, mixed, mesic, Typic Hapludult) sieved to pass a 2 mm screen. Soil (268.3g) was packed into 250ml plastic sample cups to the 178ml level to achieve a bulk density of 1.2g cm^{-3}. Water content of each cup was maintained at 80% of field capacity by adding deionized water every other day over the course of the study.

A set of samples were extracted (1:10, w/v) with 2*M* KCl after 0, 7, 14, 21, 28, 42, 56, 70, 84, and 98 days and analyzed for inorganic N (NH_4-N and NO_3-N) on a Technicon Auto Analyzer (Mulvaney, 1996).

All statistical analyses were performed using the standard procedures of SAS Version 8.0; including a test of normality before analyses were performed (SAS Institute, 1998). A quadratic plateau function, Y=A+B*X0+C*X0*X0, was fit to the data using the NLIN procedure of SAS. The model produced an estimate of maximum PAN (Y) and the amount of time (X0) required to reach PAN (NH_4-N plus NO_3-N).

3.3 Results and Discussion

The average NH_4-N concentration for each treatment at each sampling date is shown in Figure 3.1. Concentrations of NH_4-N peaked between 0d and 14d. The treatments receiving the highest rate of PPL (244 kg N ha^{-1}) peaked at 7d. By 42d, all treatments were at or near 0 mg NH_4-N kg^{-1}.

The average NO_3-N concentration for each treatment at each sampling date is shown in Figure 3.2. The general trend was a rapid increase in NO_3-N during the first 28d to 42d. This increase coincided with the rapid decrease in NH_4-N, which is explained by nitrification of NH_4-N to NO_3-N over time. Preusch et al. (2002) reported similar results from a mineralization study of composted and fresh poultry litter. These data support the practice of applying fresh poultry litter at, or close to, the time at which crops will uptake N subsequently reducing N losses due to volatilization and leaching (Preusch et al., 2002).

Amount of plant available N (PAN), which is defined as NH_4-N + NO_3-N in each treatment minus the NH_4-N + NO_3-N of the 0 kg N ha^{-1} rate, increased over time in all treatments (Figure 3.3). The data was fit to a quadratic plateau model to determine the day at which mineralization ceased and the concentration of PAN on that day for each treatment (Table 3.1). The not-mixed 244 kg N ha^{-1} treatment did not converge. It appeared that mineralization continued at a very slow rate in this treatment. For the remaining treatments, R^2 values ranged from a low of 0.63 to a high of 0.90 indicating that mineralization increased rapidly and leveled off within 98d. Time required to reach maximum PAN ranged from 38d to 98d, increasing with N rate.

Concentrations of PAN were converted from mg kg^{-1} to mg and divided by initial mg of total N applied to produce percent PAN (Table 3.2). Percentage of PAN ranged from 43.2 to 54.5 (LSD= 5.8%); there was no correlation with increasing

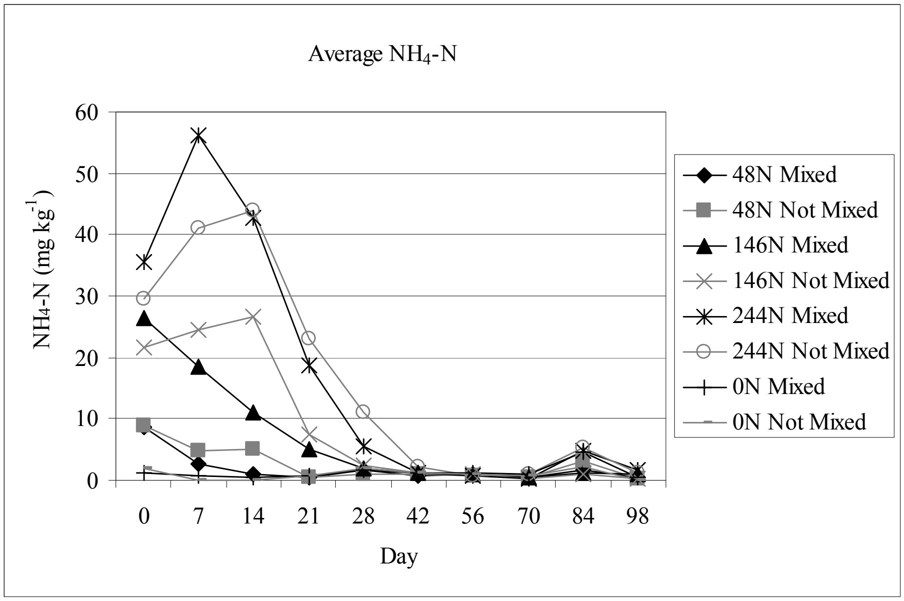

Figure 3.1. Average plant available NH_4-N concentration for each treatment and each sampling date (0, 7, 14, 21, 28, 42, 56, 70, 84, and 98d).

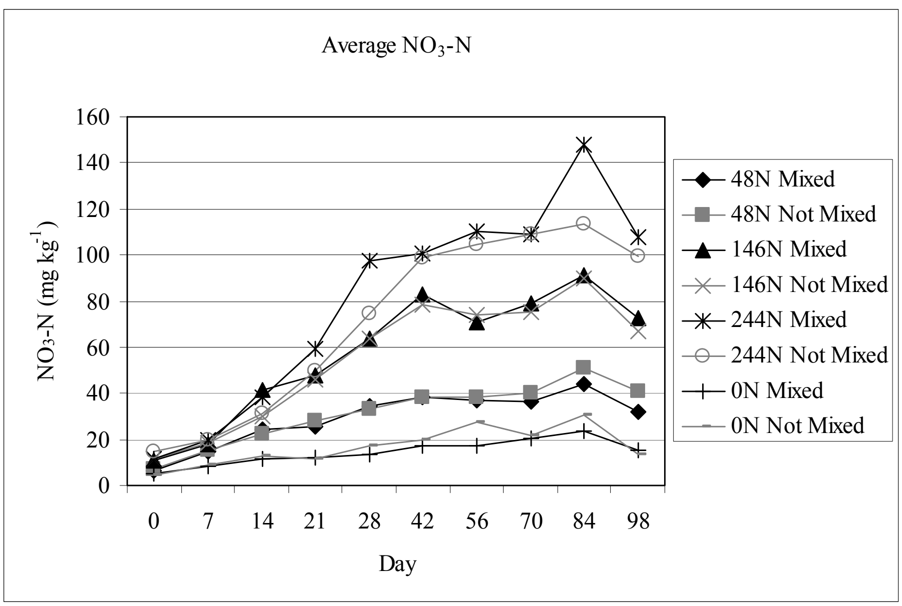

Figure 3.2. Average plant available NO_3-N concentration for each treatment and each sampling date (0, 7, 14, 21, 28, 42, 56, 70, 84, and 98d).

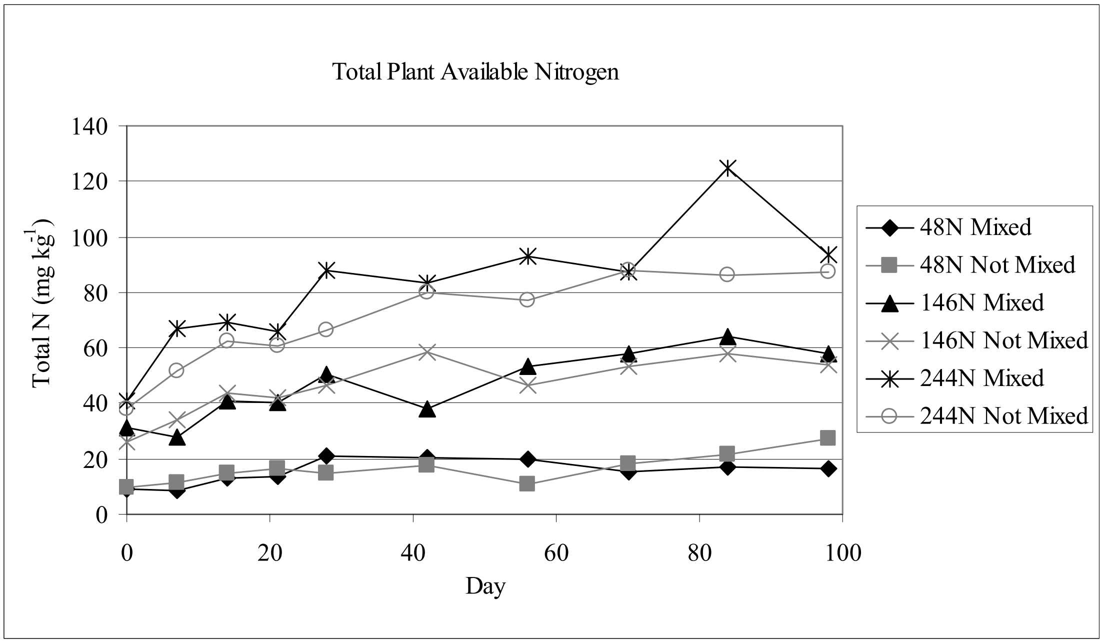

Figure 3.3. Total plant available nitrogen (NH_4-N + NO_3-N) from PPL for treatments 48, 146, and 244 kg N ha^{-1} incorporated or topdressed, for each sampling date (0, 7, 14, 21, 28, 42, 56, 70, 84, and 98d).

Table 3.1. Model parameters for the quadratic plateau model† used to predict percent plant available N for the three N rates, mixed or not mixed.

Treatments kg N ha^{-1}	R^2	A	B	C	YP= Total N at Critical Point ---mg kg^{-1}---	X0= Critical Point Day
			Mixed			
48	0.63	0.90	0.04	-0.00053	16.9	38.5
146	0.88	2.51	0.10	-0.00072	59.1	68.6
244	0.80	5.07	0.11	-0.00058	106.2	98.1
			Not Mixed			
48††						
146	0.78	2.61	0.11	-0.00104	52.9	50.6
244	0.90	4.02	0.14	-0.00111	86.0	64.1

† Quadratic plateau model, A+B*X0+C*X0*X0
††Model did not converge

Table 3.2. The amount of plant available N, amount of initial N, and percentage of plant available N for 48, 146, and 244 kg N ha^{-1}, mixed or not-mixed.

Treatment ---kg N ha^{-1}---	PAN -------mg-------	Initial N -------mg-------	PAN†† -------%-------
		Mixed	
48	4.5	10.3	43.2
146	15.6	30.8	50.6
244	28.0	51.2	54.5
		Not Mixed	
48†			
146	14.0	30.8	45.3
244	22.7	51.2	44.1

† Model did not converge

†† LSD=5.8%

N rate. A comparison of the two highest N rates suggests that incorporation (mixing) increases PAN. Overall, results from this study indicate that 50% PAN is a reasonable estimate for PPL.

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