COOL-SEASON TURFGRASS RESPONSE TO BIOSOLID FERTILIZATION IN THE PACIFIC NORTHWEST

By

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Abstract

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Turfgrass response to nitrogen (N) can be affected by N source and season of application. Field and laboratory studies were conducted at Puyallup, WA to compare turfgrass response measured by N recovery, visual color and quality, and N release of turfgrass fertilizers. Nitrogen sources were applied to a fine-fescue (*Festuca rubra* L.) / colonial bentgrass (*Agrostis capillaris* L.) mixture grown on a sand cap maintained under golf course fairway conditions and perennial ryegrass (*Lolium perenne* L.) grown on a Puyallup fine sandy loam soil maintained under home lawn conditions.

In the field, month of application and N source were found to affect turfgrass response. Efficiency of ammonium sulfate (AmS), polymer-coated sulfur-coated urea (PCSCU), and biosolid N sources was increased when applications were made corresponding to plant growth cycles and periods of expected active microbiological activity. Effective late fall N use from biosolid fertilization of perennial ryegrass was noted.

Limited availability of complex N forms associated with biosolid N sources produced overall less turfgrass response. However, similar turfgrass response to N sources was noted when higher biosolid N rates were applied to perennial ryegrass turf. Generally N recovery and visual quality were highest 4 wk after N source application.

A laboratory incubation study was conducted to compare N release rates of fertilizers containing various organic N sources. Product composition appeared to have an effect on inorganic N release ($NH_4^+ + NO_3^-$). As N solubility increased, total N extracted increased. A large fraction of inorganic N was collected after the first week of incubation.

Nitrogen source affected the amount of inorganic N released. Higher amounts of inorganic N were extracted from AmS and PCSCU fertilizers while less was extracted with Nutri-Rich 4, Milorganite® and Soundgro™. Inorganic N release was found similar for anaerobically digested biosolids and dried poultry waste alone. Inorganic N release was better estimated via fertilizer C:N ratio than N source materials.

Seasonal turfgrass response and N availability are important factors to consider when selecting N fertilizers. Higher rates of applied biosolids may be needed to account for decreased first year N availability.

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Dedication

This thesis is dedicated to my mother and father, Susan and Keith Rutan,
who provided me with the needed friendship, emotional, and financial support.

INTRODUCTION

A main goal in turfgrass management is to efficiently produce healthy turf that is green and aesthetically pleasing and can withstand the rigors of use. Levels of maintenance can vary widely with turfgrass and setting. For many years turfgrass managers have used additional nutrient inputs to supplement those provided by the growth medium. Of those nutrients applied, N is often applied in the largest amount. Nitrogen is responsible for turf color and density, encourages recovery from stress and damage, and promotes vigorous, healthy growth and development. It is also a vital component of chlorophyll, amino acids, nucleic acids, enzymes and vitamins. How turfgrass obtains N is a highly complex cycle, including transformations among air, soil, and water. A thorough understanding of N cycling is necessary for turfgrass managers to make sound environmental decisions.

Nitrogen cycle

Nitrogen can be found in soils as organic and inorganic N. The size and turnover rates of N pools are important in determining N availability. Primary N pools consist of N_2, organic N (contained in plants, animals, microbial biomass, and soil organic matter), and NH_4^+ and NO_3^- ions (Myrold, 2005). The sizes of these pools can vary, but inert dinitrogen gas comprises the largest followed by soil organic N. Most of the N in surface soils is found in organic form consisting of proteins (20 to 40%), amino sugars such as hexosamines (5 to 10%), purine and pyrimidime derivates (≤1%), and complex unidentified compounds, resulting from the reaction of NH_4^+ and lignin, polymerization of quinones with N compounds and condensation of sugars and amines (Tisdale and Nelson, 1975; Cleemput and Boeckx, 2006). Subsoils contain an important fraction of the total soil N present held by the soil exchange complex or trapped as non-exchangeable NH_4^+ in interlayers of nonexpanding 2:1 clay lattices thus rendering it unavailable (Balogh and Walker, 1992; Cleemput and Boeckx, 2006). The plant biomass N pool is intermediate in size and is a function of vegetation type, climate, and soil N availability (Myrold, 2005). Soil inorganic N consisting of NH_4^+, NO_2^-, NO_3^-, N_2O, and NO, collectively, is the smallest pool, rarely exceeding 100 mg kg^{-1} in the plow layer of fertile agricultural soils (Tisdale and Nelson, 1999; Myrold, 2005). Turnover rates are slowest for the larger N pools, requiring millions of years for N_2 while soil organic N may take only decades. Plant biomass N turns over annually while soil inorganic N may turn over more than once a day (Myrold, 2005). Nitrogen can be made available by the microbial biomass from organic substrate mineralization or microbial N turnover. This is a dynamic N pool, and has been observed to change rapidly (Fisk and Schmidt, 1995).

Nitrogen cycling in terrestrial ecosystems is a biogeochemical cycle which encompasses internal and external N cycles describing the transformations of N from one form to another (Hart et al., 1994). External N cycling describes processes such as N_2 fixation, N deposition, N fertilization, N leaching, runoff, erosion, denitrification, and NH_3 volatilization which affect N loss or gain in ecosystems. Internal N cycling processes including plant assimilation of N, N additions to soil from plant and root turnover, N mineralization, and fixation of N_2 gas to N-oxides (by *Rhizobia*, free-living soil microorganisms, atmospheric electrical discharges, or manufacture of synthetic products) are responsible for chemical N conversions and N transfer from one ecosystem pool to another (Hart et al., 1994; Cleemput and Boeckx, 2006). Microbes and chemical processes mediate the transformation from one form to another. Direct N losses consist of NO_3^- leaching, denitrification, volatilization, and plant biomass removal (Havlin et al., 1999; Cleemput and Boeckx, 2006).

The conversion of organic N from soil organic matter and plant residues to inorganic nitrogen NH_4^+ and NH_3 is a three step process known collectively as mineralization (Tisdale and Nelson, 1975; Carrow et al., 2001, Wiederholt and Johnson, 2005). Heterotrophic microorganisms decompose organic proteins releasing amines and amino acids (Havlin et al., 1999). These organic N compounds are mineralized to NH_3 and NH_4^+ (ammonification), a process mediated by microbial extracellular enzymes (Myrold, 2005). As microbial activity increases more NH_4^+ is produced (Wiederholt and Johnson, 2005). Significant relationships of net N mineralization with soil water, temperature, and microbial biomass have been observed (Fisk and Schmidt, 1995). Mineralization was increased by increasing soil temperatures from 3°C to 15°C in a laboratory incubation study by Andersen and Jensen (2001). Mineralization is also affected by soil pH. Garau et al. (1986) observed higher rates of mineralization in soil of pH 7.8 vs. a soil of pH 5.5. The last step of mineralization is nitrification, the conversion of NH_4^+ through NO_2^- to NO_3^-. Obligate autotrophic nitrifying bacteria oxidize NH_4^+ to NO_2^- (*Nitrobacter* sp.) followed by a second group of obligate autotrophic bacteria that oxidize nitrite to NO_3^- (*Nitrosomonas* sp.) under optimal environmental conditions (Hooper et al., 1997; Cleemput and Boeckx, 2006). These bacteria perform best in warm temperatures (20 to 40°C), and aerated bulk soils at near field capacity (-33 kPa in medium- to heavy-textured soils, to 0 to -10 kPa in light sandy soils) (Myrold, 2005; Cleemput and Boeckx, 2006). Nitrification is relatively constant around neutral pH, though at low pH (<5.5) an autotrophic nitrifier, *Nitrosospira* sp., has been found to oxidize NH_4^+ (Boer and Kowalchuk, 2001). As this is an aerobic process, soil oxygen levels will affect nitrification. High rates of nitrification usually occur when soil oxygen is 10 to 20% by volume, while below 5% the rate declines rapidly (Tisdale and Nelson, 1975; Carrow et al., 2001).

Substrate elemental composition can affect mineralization and immobilization. As organisms decompose organic matter, C and N are used as energy sources. Organic additions are commonly referred to with C:N ratios, which gives an estimate of decomposability. Organic material additions to the soil generally stimulate microbial activity and growth. Easily decomposable compounds such as simple carbohydrates, nucleic acids, amino acids, proteins, and lipids initiate microbial decomposition (Shi et al., 2006). In turfgrass, clipping return can affect microbial activity. Clippings have been found to contain easily-decomposable compounds. Their decomposition and mineralization was observed rapid upon return to the soil (Shi et al., 2006). Where substrate C is low, increased amounts of NH_4^+ and NO_3^- have been found (Agehara and Warncke, 2005; Gale et al., 2006). It is generally accepted that organic amendments with a C:N ratio ≤20:1 will result in net NH_4^+ production. When available N becomes part of the soil microbial biomass, a temporary reduction of inorganic N can occur called immobilization (Wiederholt and Johnson, 2005). Organic amendments containing cellulosic wastes are likely to have an immobilizing effect (Van Kessel et al., 2000). It is generally accepted that materials with a C:N ratio >20:1will result in immobilization. In some cases, easily decomposable fractions may contain higher C:N than the whole-plant material. Short-term immobilization has been observed to occur with easily-decomposable compounds (Andersen and Jensen, 2001). To become available again, immobilized N must be released by microbial action.

Nitrogen fate

The fate of N in the environment is important in turfgrass management from both an environmental and economic standpoint. There are several fates to which N can be subjected. These include NO_3^- leaching, denitrification, NH_3 volatilization, clipping disposition, and immobilization to the surrounding environment (Hull and Liu, 2005). Nitrogen's mobility in soils requires careful management. An understanding of these processes can help to reduce N loss and subsequent environmental and economic losses.

Leaching studies have shown wide variation from little or no leaching to as high as 80% of applied in N (Starr and DeRoo, 1981; Petrovic et al., 1990). Nitrogen and water inputs are required for the maintenance of high quality turfgrass. According to Petrovic (1990) the combination of both under certain conditions can lead to leaching of N, especially in NO_3^- form. Generally leaching is most likely to occur in sandy soils fertilized with high rates of soluble N and rainfall or irrigation is excessive (Hull and Liu, 2005). Soils consist of negatively charged mineral and organic particles, their total measure referred to as the cation exchange capacity (Wiederholt and Johnson, 2005). The soil exchange sites typically attract NH_4^+, while NO_3^- is repelled making it relatively mobile in the soil. Coarse textured soils have lower water holding capacity and a greater potential for NO_3^- leaching (Carrow et al., 2001; Wiederholt and Johnson, 2005). Physical amendments can be used to improve root-zone structure and water retention of sandy soils, and reduce N leaching losses. These include sphagnum peat and clay (Whitmyer and Blake, 1989; Brauen and Stahnke, 1995). Besides soil texture, leaching is controlled by other factors including amount and intensity of rainfall, fertilizer N form (Shuman, 2003), irrigation frequency and quantity (Brown et al., 1977; Morton et al., 1988), temperature (Cleemput and Boeckx, 2006), and plant density (Easton and Petrovic, 2004).

Nitrate leaching can be a significant loss pathway for fertilizers with urea components (Frank et al., 2006). Surface applied urea rapidly hydrolyzes to $(NH_4)_2CO_3$ and a significant amount can be volatilized if no turf cover is present (Tisdale and Nelson, 1975). Brown et al. (1982) found greater NO_3^- concentrations in leachate from soil greens treated with NH_4NO_3 than from Milorganite, a natural organic source of N. Frank et al. (2006) concluded single dose, water-soluble N applications (49 kg N ha^{-1} $application^{-1}$) to mature turfgrass stands should be avoided to minimize NO_3^- leaching. This was confirmed by Mangiafico and Guillard (2006). Other studies have suggested the use of organic sources or greater amounts of N to be supplied in slow release form to minimize this risk (Brown et al., 1977; Hummel and Waddington, 1981; Brown et al., 1982; Petrovic 1990; Brauen and Stahnke, 1995; Elliot and Des Jardin 1999; Guillard and Kopp, 2004). Brown et al. (1977) suggested when irrigation was kept near evapotranspiration (sum of evaporation and plant transpiration) the loss of NO_3^- from soluble inorganic N sources were minimized.

Turfgrass has been found to decrease runoff (Shuman, 2003) and promote infiltration of water. Morton et al. (1988) demonstrated water infiltration capacity of turf in a Rhode Island study with a 90% Kentucky bluegrass (*Poa pratensis* L.) and 10% red fescue (*Festuca rubra* L.) stand grown in a sandy loam soil on a 2 to 3% slope. Nitrogen was applied at three rates (0, 9.7, and 24.4 g N m^{-2} yr^{-1}) and subjected to overwatering of

3.75cm wk^{-1} plus rainfall. Measured runoff was recorded for two yr during which none of the N treatments ever exceeded the 10 mg N L^{-1} U.S. drinking water standard. In fact, mean annual flow weighted concentrations of inorganic N ranged from 0.36 mg L^{-1} on the overwatered, unfertilized control to 4.02 mg L^{-1} on the overwatered, high N treatment.

Once mineralized, NO_3^- is subject to denitrification. This is the bacterial reduction of NO_3^- to gaseous N products such as N_2 and N_2O, and is favored by anaerobic soils (Myrold, 2005; Wiederholt and Johnson, 2005). Under waterlogged conditions, denitrifying bacteria use NO_3^- instead of oxygen for energy (Wiederholt and Johnson, 2005). However, denitrification can also occur in aerobic soils. Developments of "hot-spots" were observed in the vicinity of particulate organic C where decomposition activity apparently increased O_2 consumption, as evidenced by increasing amounts of CO_2 (Parkin, 1987). Increasing N rates have also been found to enhance denitrification (Ryan et al., 1973).

Volatilization can be another avenue of N loss in a turfgrass system. This is the transformation of NH_4^+ to NH_3 which increases with increasing soil pH, temperature, soil porosity, and wind speed at the soil surface (Wiederholt and Johnson, 2005; Cleemput and Boeckx, 2006). Some turfgrass fertilizers are available in NH_4^+ forms and urea. When these are applied, urea is hydrolyzed by the enzyme urease to CO_2 and NH_3 which is then subject to gaseous loss (Hull and Liu, 2005). Rates are greatest in soil pH > 7.3 and moist, humid air at temperatures up to 22°C (Titko et al., 1987; Wiederholt and Johnson, 2005). Under these conditions as much as 60% NH_3 can be lost from urea (Titko et al., 1987).

Removal of clippings can present a pathway of N loss in turf management. As N is partitioned to shoots from roots, N use efficiency is decreased through clipping removal (Jiang and Hull, 1998). Clipping N can account for contributions of both fertilizer-N and soil N. Starr and DeRoo (1981) concluded that retaining clippings on turf can permit the reduction of annual N requirements by one-third. They applied annual organic fertilizer-N at 195 kg ha^{-1} during the first two years of a field study and ^{15}N-labeled inorganic fertilizer-N at 180 kg ha^{-1} the third yr, both rates applied in split applications during May and September. Clipping analyses indicated that leaf tissues contained equal amounts of fertilizer N and soil derived N when clippings were not returned. Where clippings were returned, tissue yields increased by one-third and clipping N was derived in equal amounts from soil, fertilizer, and grass clippings.

Finally, N applied to turfgrass can be subjected to immobilization resulting in reduced plant available N. While this is typically an avenue of loss in turfgrass, it has been viewed as an important mechanism of N retention in pine forest harvest (Vitousek and Matson, 1983). The pathway N takes in turf originates in its assimilation in grass leaves, and subsequent transport to grass roots after which root cells are sloughed and incorporated into soil organic matter (Hull and Liu, 2005). Rates of N immobilization have been found in some cases comparable to N mineralization rates (Shi et al., 2006). In other cases, 20 to 25% of fertilizer N can be incorporated into soil organic matter during a single growing season (Starr and DeRoo, 1981; Miltner et al., 1996).

Nitrogen sources

Providing the least amount of fertilizer input to sustain desirable turf quality is an important attribute to any N fertilizer program. Turf managers are often challenged with maximizing fertilizer use efficiency while reducing runoff and pollution to groundwater. A variety of fertilizer technologies have been developed to help meet these needs. The mechanism by which N is supplied can be divided into two categories: slow-release, or controlled-release, and readily available. Slow-release sources can further be divided into natural organics, synthetic organics, and coated soluble N sources. Natural organics are a group of slow-release fertilizers conforming to the Association of American Plant Fertilizer Control Officials definition as “material derived from either plant or animal products containing one or more elements other than carbon, hydrogen, and oxygen, which are essential for plant growth” (Meister, 1997). Nitrogen can be found as $-NH_2$ groups and must be converted to available forms for plant absorption. Slow release N sources are made plant available via hydrolysis and dissolution, as well as mineralization. Synthetic-organic fertilizers include urea-formaldehyde reaction products (UF), which are formed from the reaction of urea and formaldehyde (Kaempffe and Lunt, 1967). Other synthetic-organic fertilizers include isobutylidene diurea (IBDU), formed from the reaction of urea and isobutyraldehyde. Urea-formaldehyde reaction products mineralize to varying degrees depending on the length of their polymer chains (Hays et al., 1965; Kaempffe and Lunt, 1967). Isobutylidene diurea is made plant available via hydrolysis. Coated products are soluble N sources coated with S, polymers, or both that act as physical barriers to delay the dissolution of N (Carrow et al., 2001).

Quick-release sources are those available for immediate plant adsorption (Bowman, 2003), usually classified according to their respective ionic form, NH_4^+ or NO_3^-. Other quick release sources include synthetic organic N sources urea (NH_2-CO-NH_2,), and soluble UF reaction products such as methylol urea and short polymer chain methylene ureas. While some UF products are considered slow to release, the ratio of urea to formaldehyde can be altered resulting in less water-insoluble N (discussed below). Mechanisms of N release for quick release N sources include both hydrolysis (urea), dissolution, and mineralization (UF products).

Solubility is a measure of a fertilizer's dissolution rate in water and generally refers to slow release synthetic sources such as IBDU (Carrow et al., 2001). Natural organic and UF products contain various fractions of water soluble N (WSN) or water insoluble N (WIN) components. Water soluble N is the N fraction soluble in cold water (25°C). This fraction is quickly plant available, but only after internal cleavage and mineralization to NO_3^- or NH_4^+ (Kaempffe and Lunt, 1967). An intermediate WIN fraction exists that is soluble in hot water (98 to 100°C), but insoluble in cold water with pH 7.5. This fraction mineralizes more slowly than that above, about 15% wk^{-1} within the first two wk of application, but declines to 1.5% wk^{-1} in the fourth to sixth month (Kaempffe and Lunt, 1967). A third WIN fraction contains N not soluble in hot water. This fraction is highest in molecular weight and slowest to release N (Hays et al., 1965). In reacted products, this portion contains longer chain polymers mineralized at a rate of about 10% yr^{-1} (Kaempffe and Lunt, 1967).

Coated products rely on moisture to dissolve an encapsulated N source (Carrow et al., 2001). Products may contain S and/or polymer protective coatings to slow the release of N. The thickness of the S coat influences release rate while the polymer slows water penetration into the S (Carrow et al., 2001). Water enters the particle through pores or surface imperfections where increasing internal pressure causes diffusion of N through coating(s). These coatings either jointly or separately determine release properties. Once the encapsulated urea prill is exposed to the environment, it is available for hydrolysis.

Biosolids in turfgrass

Biosolids have long been recognized for their N value in turfgrass fertilization. The Milwaukee Sewerage Commission inaugurated the first large scale activated sludge plant in 1923. The biosolids produced from this plant were marketed under the brand name Milorganite and found to contain 6.2% total N (5.17% being water insoluble), 2.63% available P_2O_5, and 0.4% available K_2O (http://www.milorganite.com/about/history.cfm). The Milwaukee Sewerage Commission established a fellowship at the University of Wisconsin where research was conducted under the direction of Prof. E. Truog that pertained to the use of activated sludge on golf courses (Noer, 1925). Activated sludge was found to be an effective replacement of manure in topdressing mixtures and when mixed with ammonium sulfate (AmS) was found to fix NH_3 and reduced burn potential (Noer, 1925). Turfgrass was also noted to take on a dark green color and more vigorous growth upon activated sludge application.

The term ‘biosolids’ refers to the stabilized solids from municipal wastewater treatment plants, which must meet federal regulations for land applications (USEPA, 1995). The actual sludge is not human waste. It is the dead microorganisms that digest the wastes and remove the pollutants from the treated water. Disposal of wastes to the land provides a beneficial as well as an economic method of disposal. It has long been an accepted and recognized cultural practice. Crites et al. (2000) cites accounts of sewage irrigation projects in Bunzlau, Germany in 1531, and also in Edinburgh, Scotland, 1650, where wastewater was used to fertilize vegetables.

Biosolids are known as sewage sludges prior to treatment. Sewage sludges contain the solid fraction of municipal sewer system constituents (home, commercial, and industrial discharges) (Crohn, 1995). These can be treated in a number of ways such as activation, digestion, or composting. Sludge composting is a process in which the solid portions of wastewater, or sludge, are conditioned with bulking materials such as woodchips, leaves, or refuse. Microbes then convert the sludge into a soil-like product in the presence of air and moisture (Wilson et al., 1980). More commonly, it is the biosolids that are composted rather than the raw sludge. Activated sewage sludge products are made in a microbial process. This is a four step process: screening, settling, secondary treatment, and disinfection. Secondary treatment is known as ‘activation’; the sludge is inoculated with microorganisms and aerated resulting in flocculated organic matter, which is then vacuum-filtered (Beard, 1973). Sludge decomposition can be aerobic or anaerobic. If during the treatment process the sludge is not aerated, anaerobic microbes will dominate the aerobic microbes. Anaerobic digestion is used to reduce the organic content of wastewater and produce methane gas (Crites et al., 2000). Aerobic sludges are more susceptible to microbial decomposition, and are thus not considered as stabilized as anaerobically treated sludges (Sommers, 1977).

Like Milorganite, Soundgro is a class A exceptional quality granular biosolid product. It is produced by the Chambers Creek Regional Wastewater Treatment Plant at University Place, WA. Exceptional quality refers to sewage sludge that meets EPA’s ceiling concentration limits contained in the Part 503 Rule, which concern pollutant and trace element (metal) concentration limits (USEPA, 1995). Likewise, Class B biosolids are a lesser treated form of Class A biosolids. Class A biosolids have been treated sufficiently to reduce pathogens such as *Salmonella* sp. bacteria, enteric viruses, and viable helminth ova (roundworms and tapeworms) to below detectable levels (USEPA, 1995). Class A biosolids can be land applied without any pathogen-related restrictions. Both Milorganite and Soundgro meet class A standards through heat-drying at high temperatures. Site restrictions exist with the land application of Class B biosolids to minimize the potential for human and animal contact until environmental factors have reduced pathogens to below detectable levels (USEPA, 1995). Class B biosolids cannot be packaged for sale or to be given away for land application.

Biosolids have been found to contain both desirable and undesirable properties when used as a turfgrass N source. Since the majority of the N is found in organic forms, about 80%, and about 20% in mineral forms (Sommers, 1977), biosolids serve as a source of slow release N. Nitrogen is provided throughout the growing season as well as in subsequent years (Cogger et al., 1999; 2001; 2004). This is due to less available N from natural organic N sources contained in recalcitrant N forms. Cogger et al. (2004) found first year plant available N (PAN) to average 37±5% of total N from biosolids and second yr PAN to average from 8 to 25%. Similarly, Hummel and Waddington (1981) observed residual effects with use of natural organic N sources where additional N became available in subsequent years after application. Turf managers can benefit from fewer N applications at higher rates. There is less risk of N loss by leaching (Easton and Petrovic, 2004) and N volatilization (Ryan et al., 1973). Biosolids have a low salt index, resulting in little or no foliar burn (Noer, 1925; Moberg et al., 1970). The land application of sewage sludges provides a good method for waste disposal and nutrient recycling. Because of their low nutrient status, biosolids can be a relatively expensive source of nutrients. Considerably large applications are needed when used to meet plant N requirements compared to concentrated N sources. Higher transportation costs are thus a result of larger quantities to be utilized. Biosolids typically contain a close N to P_2O_5 ratio. When applications of sewage sludges are made based on plant N requirements, accumulation of P can occur in the surface soil (Cogger et al., 2001). Easton and Petrovic (2004) recovered very little applied P from repeated use of natural organic sources in clippings, runoff, or leachate suggesting the majority still remained in the soil, roots, and plant tissue, which could eventually result in massive amounts of P being subject to runoff and leaching losses. Because biosolid N has been found available in subsequent years following application (Cogger et al., 1999; 2001; 2004), the quantities of wastes that can be land applied are frequently limited by the buildup of NO_3^- in the subsoil after decomposition (Gilmour et al., 1977). An understanding of biosolid decomposition and subsequent N availability are needed to prevent applications that can exceed turf use.

Turfgrass N uptake

Nitrogen must be converted to NO_3^- or NH_4^+ ions in order to be taken up by turfgrass roots (Beard, 1973; Petrovic, 1990). Ion absorption is the primary mechanism of turfgrass nutrient uptake. Turfgrass roots are fibrous and extensive with large surface areas that can easily absorb nutrient ions and incorporate them into the root cells (Beard, 1973). Plant uptake of inorganic N is influenced by a number of factors including temperature and moisture that affect plant growth rate, genetic cultivar differences, available N pools, and N sources and rates (Petrovic, 1990; Jiang and Hull, 1998). As NO_3^- is taken up by the plant, it is reduced to NH_3 and NH_4^+ in the cytoplasm of both shoots and roots. Once reduced, N is assimilated into amino acids, a precursor for chlorophyll (Carrow et al., 2001). These amino acids can then be transported throughout the plant to support cell division and growth (Hull and Bushoven, 2007). When N is absorbed as NH_4^+ by roots, it is incorporated into organic N compounds in the root. Once in the root it is assimilated into amino acids by specific enzymes (Carrow et al., 2001).

Variation in the external N supply (NH_4^+ or NO_3^-) has been found to influence tissue and apoplastic NH_4^+ concentration differently. Ammonium concentrations in leaf tissue and apoplast increased rapidly in response to a switch from NO_3^- to NH_4^+ nutrition in stands of *Lolium perenne* L. and *Bromus erectus* Huds. (Mattsson and Schjoerring, 2002). They demonstrated that NH_4^+ is rapidly taken up from the nutrient solution and translocated in the xylem from root to shoot.

On a root weight basis, Bushoven and Hull (2001) observed perennial ryegrass (designated PR) cultivars absorbed NO_3^- at 2.56 times the mean rate of creeping bentgrass (*Agrostis stolonifera* L.) (designated CB) cultivars. However, biomass partitioning (allocation to specific plant regions) to roots was 2.46 times greater in CB vs. PR, suggesting that reduction and assimilation of N occurred in leaf tissues of PR to a greater extent. In a similar study, Bushoven and Hull (2005) observed increases in external NO_3^- concentrations to PR roots to correspond to increased leaf extractable NO_3^-, which suggested higher NO_3^- supply to roots would likely partition more NO_3^- to leaves.

Application timing

Nutrient utilization efficiency of turfgrass can be influenced by timing of fertilizer applications. Nitrogen applications made to correspond to plant growth may increase efficiency of N use. Periods of highest nutrient needs in turfgrass are found from June to July and October to November (Carrow et al., 2001). Brown et al. (1977) concluded that N losses and subsequent NO_3^- concentrations found in leachate could be lowered where N rates are decreased during periods of low plant N use. Other concerns with N utilization include overstimulation of topgrowth. Stored carbohydrates can become depleted resulting in increased susceptibility to disease and delayed summer dormancy recovery when too much N is applied during periods of high growth (Zanoni et al., 1969). This may also result in higher mowing frequency which means more maintenance cost.

Turfgrass establishment can be very sensitive to fertilizer application. A high potential for nutrient loss exists during establishment due to mineralization stimulated by soil disturbance (Mangiafico and Guillard, 2006), the sparseness of surface cover, and frequent irrigation needs. Sartain and Gooding (2000) applied N at 98 kg N ha^{-1} every week for 12 wk, recovering approximately 25% of the applied N from NH_4NO_3 in leachate, but this was reduced when digested sewage sludge (Milorganite) was mixed with IBDU. Reducing the amount of soluble N in an establishment program as well, as the incorporation of peat in a sand-based rootzone mix, can improve general appearance and reduce NO_3^- leaching (Brauen and Stahnke, 1995; Sartain and Gooding, 2000).

Turfgrass N fertilization has been a highly evolving area with changes in fertilizer technology and management practices. Seasonal N cycles can influence application timing. Periods of low temperatures characterized by low microbial activity may not be fertilized the same as warmer periods. Miltner et al. (2001) concluded that April, June, and September were the most effective times to fertilize perennial ryegrass (PR) as measured by clipping N content in the Pacific Northwest. However, the study also concluded that repeated monthly N applications of 49 kg ha^{-1} (392 kg N ha^{-1} yr^{-1}) did not promote effective use of fertilizer N as evidenced by rapid accumulation of soil NO_3^- in the fall.

Application of N can also affect turf disease. Fall fertilization has been proven to aid red thread [*Laetisaria fuciformis* (McAlpine) Burds] suppression and enhance winter/post-winter spring turfgrass quality (Miltner et al., 2004) and color (Ledeboer and Skogley, 1973; Mangiafico and Guillard, 2006).

Effective cool-season fertilizer programs may encompass variable applications rates throughout the year. The standard has been lighter applications of N in the spring and heavier in the fall. Standard recommendations of early to late-spring applications can vary from 24.5 to 36.8 kg N ha^{-1} with mid-season to fall applications of 49.0 to 73.5 kg N ha^{-1} for a total annual rate of 147 to 245 kg N ha^{-1}. Summer N fertilizer applications should be made with caution as heat and drought stress can be increased causing periods of low growth (Beard, 1973). Light applications of soluble N sources, or fewer heavier applications of slowly available sources have resulted in a uniform turfgrass growth response (Moberg et al., 1970). In a 3-yr field study conducted by Wehner et al. (1993) N was supplied to turf at 49.0 and 98.0 kg ha^{-1} (196 kg N ha^{-1} yr^{-1}) monthly October through January. Acceptable turfgrass color was obtained the following spring when N was supplied as urea though this was improved when applied in December and January.

When supplied as biosolid N (Milorganite) lower yields were obtained and also acceptable color (higher N rate) at all application dates.

Light and frequent applications of slow-release N sources can provide excellent protection from NO_3^- leaching (Brauen and Stahnke, 1995). Many golf course superintendents utilize spoon feeding where fertilizer is applied in liquid form due to low application rates not practical with granular sources. Nitrogen rates in a spoon feeding program are typically 4.9 to 12.3 kg N ha^{-1}. Brauen and Stahnke (1995) found 17.6 kg N ha^{-1} (392 kg N ha^{-1} yr^{-1}) applied in 2-wk intervals quite favorable to bentgrass and annual bluegrass growth in putting greens under play in the Pacific Northwest. The flexibility of a spoon feeding program allows it to be adjusted to meet specific needs of an area being treated.

Application timing can also influence N leaching. In the Pacific Northwest, highest concentrations of NO_3^- in leachate have been found to occur during the rainy winter months between late fall and early spring (Brauen and Stahnke, 1995; Johnston and Golob, 2003). Subsequently, late fall N applications have been the subject of much research. Brown et al. (1977) concluded potential for groundwater pollution was greatest in winter where highest NO_3^- concentrations were found. This was attributed to periods of low plant growth and higher volumes of runoff. Guillard and Kopp (2004) observed a greater percentage of NO_3^- leaching events occurring between late fall and early spring in cool-season turfgrass. Nitrogen was applied as AmS, polymer-coated sulfur-coated urea (PCSCU), and an organic fertilizer at 147 kg N ha^{-1} yr^{-1} split into three applications of 49.0 kg N ha^{-1} with 17% of applied N recovered in leachate. Miltner et al. (1996) used ^{15}N-labeled urea (LFN) applied to Kentucky bluegrass turf to monitor leaching. Two treatment schedules were used: the spring treatment utilized five 39.2 kg N ha^{-1} applications made from late April through late September and the fall treatment utilized the same application frequency applied from early June to early November. Total annual N applied was 196 kg N ha^{-1}. Total recovery of LFN was 64 and 81% for spring and fall treatments, respectively, recovered mainly as thatch and clippings and only 0.23% as leachate. The study concluded limited potential for NO_3^- leaching.

Turfgrass response to N fertilization

Many fertilizing programs encompass both slow- and quick-release N sources. Slow-release fertilizers can provide a low, uniform supply of N through the growing season (Landschoot and Waddington, 1987) as well as reducing or eliminating NO_3^- leaching (Balogh and Walker, 1992; Brauen and Stahnke, 1995). Soluble N sources tend to result in quicker turfgrass response with higher uptake N uptake rates immediately after application (Landschoot and Waddington, 1987).

Some slow release fertilizers may not be available quickly enough to be utilized by turfgrass before cold temperatures slows their growth. Wehner et al. (1988) found IBDU to be ineffective for late fall N fertilization. Miltner et al. (2004) found similar results and recommended the use of AmS, PCSCU, and polymer-coated urea (PCU) for late fall fertilization of cool-season turfgrass in western Washington. In their study, a better early winter response was observed with PCSCU, while a better extended response in the spring was found with PCU. The IBDU fertilizer was not found to improve winter turf quality.

Turf response to N source additions has varied depending on a number of factors including N carrier, soil and air temperatures, amount of rainfall and applied irrigation, and frequency of application. Johnston and Golob (2003) recovered 48% of applied N from ‘Penncross’ creeping bentgrass (*Agrostis stolonifera* L.) clippings applied via urea-based granular and foliar applications at annual rates of 167 to 206 kg N ha^{-1} over a 3-yr period. Similarly, Hummel and Waddington (1981) recovered 47% and 48% of applied N when applications were made via fine-grade IBDU (31-0-0) and AmS (21-0-0) respectively, but only 29% when sewage sludge N (6-0.9-0) was used as a fertilizer source. In another study conducted by Moberg et al. (1970), higher N recoveries were observed with the use of urea and coated urea products (52% and 54% respectively) vs. sewage sludge (27%). Carrow et al. (1997) observed lower initial and residual quality on bermudagrass (*Cynodon dactylon* L.) following the application of two natural organic N carriers (Milorganite Classic 6-2-0, and Ringer Lawn Restore 10-2-6) as compared to urea.

Nitrogen recovery in clippings is used as an indication of when N becomes available from various N sources (Hummel and Waddington, 1981; Petrovic 1990). Grass species, use patterns, soil type, season, temperature, and irrigation have an impact on fertilizer N recovery in clippings (Hummel and Waddington, 1981; Petrovic, 1990). When N recovery was expressed as a percentage of N applied, Hummel and Waddington (1981) found this was an indicator of turf response because it directly correlated with clipping weight.

Tissue testing is commonly used by turf managers to monitor leaf N status (Mattsson and Schjoerring, 2002). Monitoring leaf N status can be used to verify nutrient uptake, as nutrient additions can be made without improvement in turfgrass color and quality (Hall, 1975). In a study by Mattsson and Schjoerring (2002), NH_4^+ concentration was found to be more pronounced in the apoplast than in leaf tissue. This indicated the apoplastic NH_4^+ pool to be highly dynamic and a better indicator of changes in external N supply. Cool-season turfgrass plants generally have leaf N concentrations of 3 to 4.8% (on a dry weight basis) across a wide range of genomes (Emmons, 2000; Appendix Table 3). Optimum leaf tissue N contents for healthy turf have been found to be: 2.4 to 8.3% for creeping bentgrass, 3.3 to 5.1% for perennial ryegrass, and 2.5 to 5.1% for Kentucky bluegrass (Mills and Jones, 1996). Miltner et al. (2001) found perennial ryegrass clipping N concentrations up to 6.1% when a single 49 kg N ha^{-1} application was made in November. This appeared to correspond to increased soil inorganic N values observed in October and November (Miltner et al., 2001). High soil inorganic N relative to perceived N uptake could promote leaching. When N becomes limited, chlorophyll levels are reduced, resulting in a loss of green color and reduced growth (Carrow et al., 2001).

Visual color and quality ratings are used to assess turfgrass appearance in research. Beard (1973) defined visual quality as the integrated value of shoot density, color, uniformity, and growth habit. Color is frequently used to determine the timing of N applications (Beard, 1973). As N is increased there is a linear chlorophyll content increase, as well as a similar increase in shoot growth (Carrow et al., 2001; Mangiafico and Guillard, 2005; 2007). Qualitative data is used to substantiate findings in turfgrass research though interpretations of such can lack consistency because of the subjective nature of these evaluations (Trenholm et al., 1999). More precise quantitative methods can be used to make such measurements. Chlorophyll content has been used as an indicator of N status. Handheld reflectance meters have been used to monitor chlorophyll contents (Mangiafico and Guillard, 2005) and rapidly assess plant N status (Piekielek and

Fox, 1992; Kruse, 2006; Ziadi, 2008). These devices measure optical density at two wavelengths and convert this to an index positively correlated with chlorophyll concentration (Mangiafico and Guillard, 2005) and leaf N concentrations (Mangiafico and Guillard, 2007).

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CHAPTER I

FIELD EVALUATION OF BIOSOLID, AMMONIUM SULFATE, AND POLYMER-COATED SULFUR-COATED UREA FERTILIZER APPLICATIONS TO COOL-SEASON TURFGRASSES

ABSTRACT

SoundGro™ is a heat-dried biosolids fertilizer produced by the Chambers Creek Regional Wastewater Treatment Plant (University Place, WA). Two experiments were conducted to compare the effectiveness of Soundgro to other N sources, and determine how application timing will affect turfgrass response to Soundgro in order to develop seasonal use guidelines. The first experiment (designated FW) consisted of a fine-fescue (*Festuca rubra* L.) / colonial bentgrass (*Agrostis capillaris* L.) mixture grown on a sand cap maintained under golf course fairway conditions. The second experiment (designated HL) consisted of mature perennial ryegrass (*Lolium perenne* L.) grown on a Puyallup fine sandy loam maintained at home lawn conditions. Nitrogen sources consisted of polymer-coated, sulfur-coated urea (designated PCSCU), ammonium sulfate (designated AmS), Milorganite® (biosolid; Milwaukee Metropolitan Sewerage District), Soundgro (biosolid; Pierce County, WA), and an unfertilized control. Each N source was applied as a single, monthly application to individual plots in March, May, July, September, or November at 4.9 g N m^{-2} (increased to 7.35 g N m^{-2} for HL biosolids plots). Turfgrass response was measured at 4, 8, 12, and 16 wk after treatment (WAT) as visual color and quality, chlorophyll meter index readings, leaf tissue N content, clipping yield, and N recovery (leaf tissue N content x clipping yield). Nitrogen sources applied in May were most effective producing periods of high N recovery and visual turfgrass ratings. Conditions during this time were presumably favorable to mineralization and plant growth. November applications resulted in the least turfgrass response while March, July, and September produced intermediate results. Soundgro and Milorganite N sources produced similar turfgrass N recovery, and visual color and quality ratings as AmS, and PCSCU on the HL experiment. This justified the increase in biosolid N rates. Biosolid N sources produced less response on the FW experiment due to limited availability of complex N forms. Generally, turfgrass N recovery and visual quality were increased 4 WAT. Effective late fall N use from biosolid fertilization of perennial ryegrass was noted, but AmS and PCSCU would be better choices when applied to a fine-fescue / colonial bentgrass mixture grown on a sand-cap fairway.

Abbreviations: FW, first experiment maintained at fairway conditions; HL, second experiment maintained at home lawn conditions; PCSCU, polymer coated sulfur coated urea; AmS, ammonium sulfate; N, nitrogen; WAT, weeks after treatment.

INTRODUCTION

As one of the major landscapes in America, turfgrass covers more than 50 million lawns and 14,000 golf courses (Emmons, 1995). In order to maintain turfgrass quality levels found with lawns and golf courses, managers often apply N fertilizer in addition to natural organic and inorganic pools supplied by the environment. Nitrogen influences shoot and root growth, density, color, disease susceptibility, temperature and drought hardiness, and recuperative potential (Beard, 1973). Turfgrass has an extensive and fibrous root system with which it obtains N in inorganic form (NH_4^+, NO_3^-) necessary for growth (Mattsson and Schjoerring, 2002). A variety of N sources are available to help turfgrass managers meet plant N demands. However, N sources can vary in their N release mechanisms, affecting plant N availability. Knowledge of these release patterns is needed to determine proper application timing and frequency of N sources.

Mechanisms of N release can vary among N sources based on release rates. These are usually divided into two categories: readily available or slow (controlled) release.

Slow-release N sources can further be divided into natural organics, synthetic organics, and coated soluble sources. These N sources are made plant available via hydrolysis and dissolution, as well as mineralization. Natural organics are a group of slow-release fertilizers conforming to the Association of American Plant Fertilizer Control Officials definition as “material derived from either plant or animal products containing one or more elements other than C, H, and O, which are essential for plant growth” (Meister, 1997). Nitrogen is usually present in $-NH_2$ groups and must be converted to available forms for plant absorption. Synthetic-organics include urea-formaldehyde reaction products (UF), and isobutylidene diurea (IBDU). Urea formaldehyde reaction products mineralize to varying degrees depending on the length of their polymer chains (Hays et al., 1965; Kaempffe and Lunt, 1967). Isobutylidene diurea is made plant available via hydrolysis. Coated products such as polymer-coated sulfur-coated urea (PCSCU) are soluble N sources coated with S, polymers, or both that act as physical barriers to delay the dissolution of N.

Quick-release N sources are generally referred to as soluble or readily-available. These sources are well known for their immediate plant adsorption (Bowman, 2003). However, an increased N leaching potential has been observed where the sources are applied to sand-based soils (Brown et al., 1977). Many of these sources are found in ionic form as NH_4^+ or NO_3^-. Other quick release sources include synthetic organic N sources urea [NH_2-CO-NH_2] and soluble UF reaction products such as methylol urea and short polymer chain methylene ureas. While some UF products are considered slow to release, the ratio of urea formaldehyde can be altered resulting in less water-insoluble N. Mechanisms of release include both hyrolysis (urea) and mineralization (UF products).

Biosolids are a source of natural organic N used in turfgrass fertilization (Noer, 1925; Moberg et al., 1970; Hummel and Waddington, 1981; Kiemnec et al., 1987; Landschoot and Waddington, 1987; Carrow, 1997; Elliott and Jardin, 1999; Davis and Dernoeden, 2002; Blume et al., 2009). These are the stabilized solids from municipal wastewater treatment plants, which must meet federal regulations for land applications (USEPA, 1995). Use of biosolids as fertilizer can be an effective way of recycling nutrients while providing an economic benefit for biosolid producers. Potential benefits of biosolid N include a source of slow release N (Carrow et al., 1997), negligible volatilization (Ryan et al., 1973), low N leaching potential (Easton and Petrovic, 2004) and low salt indices reducing foliar burn (Noer, 1925; Moberg et al., 1970). Disadvantages of biosolid fertilizers include low total N and decreased first year N availability. Cogger et al. (2004) found first year plant available N (PAN) to average 37 ± 5% of total N from biosolids and second year PAN to average from 8 to 25%.

Extensive research on turfgrass fertilization has been conducted assessing turfgrass response to N fertilizers of varying N sources. These responses can include turfgrass color, turfgrass quality (which can sometimes include the effect of color), clipping yields, and N recovery.

Periods of high growth and color response have been found by Landschoot and Waddington (1987) following N fertilization. Readily-available sources of N generally resulted in higher clipping yield and better color response than natural organic N sources (Hummel and Waddington, 1981; Landschoot and Waddington, 1987). In addition, periods of high N uptake were associated with periods of high color and clipping yields (Landschoot and Waddington, 1987). Turfgrass quality has been increased when N sources were applied in May and August vs. September and November, but was accompanied by excessive topgrowth (Ledeboer and Skogley, 1973). Lower acceptable turfgrass quality compared to that obtained for urea fertilized turf, and less shoot growth has been observed when turfgrass was fertilized with biosolids (Carrow, 1997). However, when additions of quick release N were added to the biosolid, initial and intermediate quality was found to compare favorably with urea. Lower N recovery was observed by Moberg et al. (1970) during biosolid application to Kentucky bluegrass. Approximately 27% of N was recovered from biosolids, while 52% was observed with urea.

Providing the least amount of fertilizer input to sustain desirable turf quality is an important attribute to any N fertilizer program. Knowledge of N availability and seasonal turf demands can aid turfgrass managers in supplying adequate N levels without compromising environmental integrity while maintaining acceptable turfgrass quality. In this experiment, field studies were conducted using Soundgro and other N sources used in turfgrass fertilization. The objective of these assessments were to compare the effectiveness of Soundgro to other N sources, and determine how application timing will affect turfgrass response to this product in order to develop seasonally appropriate use guidelines.

MATERIALS AND METHODS

The Chambers Creek Regional Wastewater Treatment Plant (WWTP) recently began producing a biosolid fertilizer, SoundGRO™. This nutrient-rich material is the result of physical and biological treatment processes of residential and commercial wastewater. This thesis was part of an ongoing project that began in July 2006 and pertains to data generated from March 2007 through March 2009. Biosolids and other N fertilizer source applications were made to turfgrass field plots, and turfgrass color and quality, clipping yield (CY), and N recovery were assessed and compared. Seasonal use guidelines were developed for the biosolid fertilizer Soundgro.

Site Description

Two sets of field plots were established 55 km southeast of Seattle, WA (USDA Zone 8a) at the R. L. Goss Turfgrass Research Facility, located at the Washington State University Research and Extension Center at Puyallup, WA.

The first set of plots was established in May 2005. The turf area was sand based and utilized sand (Appendix Table III; V) from Pierce County's Chambers Creek Properties (approx. 32 km west of the research farm), site of Chambers Bay Golf Course. This material was transported to the research farm and used to create a plot area approximately 743 m^2 with a sand depth of 280 mm. No additions of organic matter or other amendments were made. The area was seeded with the following grass mixture (percentage by weight): 27.5% 'Shadow II' chewings fescue (*Festuca rubra* L. ssp. *commutata* [Thuill.] Nyman), 25% 'Seabreeze' slender creeping red fescue (*F. rubra* L.), 20% 'Sandpiper' chewings fescue, 20% 'Tiffany' chewings fescue (collectively designated FF), 3.75% 'SR 7100' colonial bentgrass (*Agrostis capillaris* L.), and 3.75% 'Tiger II' colonial bentgrass (collectively designated CB). The area was maintained with inorganic fertilizers and irrigation until the first experimental treatments in July of 2006. The grass was mowed at a height of 12.5mm with a reel-type Toro Greensmaster® 3000 triplex mower with clippings returned two to three times weekly. The area was designated as the fairway (FW) and designed to mimic the playable turf at the Chambers Bay Golf Course.

The second set of plots were established on a mature perennial ryegrass (*Lolium perenne* L.) (49% ‘SR 4200’, 25% ‘SR 4010’, and 25% ‘SR 4100’ w/w) stand established by seed in April 1998 at the R.L. Goss Turfgrass Research Facility. The soil was a Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic, Vitrandic Haploxerolls). These soils were deep and well-drained, developed in recent alluvium consisting primarily of sand and silt. The site was maintained with synthetic-organic fertilizers and irrigation until the first experimental treatments were applied in July of 2006. Similar to home lawns and park areas the grass was mowed at a height of approximately 44 mm with a mulching, rotary-type Jacobsen Turfcat® 428 series rotary mower every 5 to 7 days. This area was designated the home lawn (HL) study.

Initial soil samples were obtained for the two areas (FW and HL) to determine pH, nutrient status, and organic matter content (Appendix Table III).

Experimental treatments began July 2006 with the last experimental treatment applied May 2009. Climatic conditions were characteristic of the maritime Pacific Northwest. Winters in Puyallup are cool and wet, while summers are mild and dry. The mean annual temperature is 11°C with a July mean of 18°C and January mean of 4°C. The area receives an annual mean precipitation of 1020 mm, occuring mainly between October and May as rain. Supplemental irrigation was required to maintain plots, especially during the dry summer months of July and August, when rainfall averages are only 20 mm each month.

Field Experiments

These experiments pertain to treatments applied from March 2007 through November 2008 and measured through March, 2009. The two field studies were conducted concurrently to evaluate N source and application timing. Observations consisting of leaf tissue N content, CY, N recovery, visual color and quality ratings, and chlorophyll meter measurements were used to assess turfgrass response to compare fertilizer treatments and develop application guidelines for Soundgro.

These studies included two primary treatments: application timing (designated "Month") and N source arranged in a split-plot design with four replications. The Month treatment consisted of five separate dates of application: March, May, July, September, and November (Table 1.1). Month was the whole plot factor and N source the subplot factor. The subplot treatment factor (N source) contained five treatment levels designated Soundgro, Milorganite, ammonium sulfate (AmS), PCSCU, and the unfertilized control (Table 1.1). This design resulted in two components of experimental error: one associated with the whole-plot treatment factor (Month) and the other with the subplot treatment factor (N source) and interaction. Whole-plot and subplot errors were assumed to be independent, normally distributed random errors with mean zero, and homogeneity among variances. These assumptions for subplot units on the same whole-plot unit were justified with the randomization of N source treatments to the experimental units.

Fertilizers

Nitrogen source treatments consisted of PCSCU, a water-soluble urea-based [$CO(NH_2)_2$] synthetic organic N carrier containing controlled release properties; AmS

[$(NH_4)_2SO_4$], a synthetic inorganic N carrier, and two biosolid N carriers, Milorganite® and Soundgro (Table 1.1). Polymer-coated sulfur-coated urea was selected for this study as it is widely used in turf. Ammonium sulfate was selected for both its wide use in turf nutrition and soluble, quick N release. Both biosolid N sources were anaerobically digested, heat-dried sewage sludge. Milorganite is an activated sewage sludge product of the Jones Island Wastewater Treatment Plant located in Milwaukee, WI, and was purchased locally in Washington. It contains 6% total N of which 0.75% is water soluble. It has been a long used source of organic N (since the 1920's) in turfgrass fertilization (Noer, 1925). Literatures resources are plentiful on its use. Soundgro is manufactured at the Chambers Creek Regional Wastewater Treatment Plant in Pierce County, WA, and was obtained locally. This product contains 5% total N of which 1.5% is water soluble. Both biosolids were dried, granular materials. The release mechanism of both organic N sources is primarily governed by soil temperature and soil microorganism activity (Briggs and Adegbidi, 2003; Wang et al., 2003).

Milorganite, AmS, and PCSCU were chosen as industry standards for comparison with Soundgro. Having two slow-release natural organic N sources (biosolids), one quick-release inorganic N source (AmS), and one controlled-release organic N source (PCSCU), a basis of comparison amongst individual release mechanisms in the cooler Pacific Northwest climate could be established.

Experimental Treatment Application

Each N source was applied as a single, monthly application to individual plots measuring 1.2 x 1.8 m in March, May, July, September, or November using a shaker bottle. Applications were made to supply N at 4.9 g N m^{-2} $plot^{-1}$. Each plot received fertilizer during only one of these months. This method allowed the effectiveness of each fertilizer to be assessed according to its month of application. Plots were then sprinkler irrigated to prevent fertilizer burn and increase fertilizer to soil contact for all treatments. The N rate on the biosolids plots in the HL experiment was increased in July 2007 to 7.4 g N m^{-2} to compensate for limited first-year N availability of biosolid fertilizers (Cogger et al., 2004). This increased rate was not applied to FW plots due to fertilizer pick-up and spread from low mowing heights. Since biosolid N sources contained a low total N content (Table 1.1), larger amounts of this product were required to achieve the desired N rate. This led to spread and pickup of biosolids by mowers on FW plots. Because fertilizers were applied based on N, differences in P and K had to be balanced between N source treatments. Additions of P and K were made as applications of triple super phosphate (19.8% P) and/or muriate of potash (41.5% K) at the time of N treatment to achieve equal P and K application rates between individual plots. Control plots received a single P and K application quantitatively equal to treated plots.

Data Collection

Observation dates occurred at 4, 8, 12, and 16 wk after treatment (WAT). Thus observations for March treatments encompassed the period of March to July, May treatments from May to September, July treatments from July to November, September treatments from September to January, and November treatments from November to March. Inclement weather sometimes prevented clipping collection and subsequent N analysis. Missing data points were the result of long periods of rainfall from October to March, typical of the Pacific Northwest maritime climate.

Qualitative analyses were performed at 4, 8, 12, and 16 WAT immediately prior to harvest. These included visual ratings of turfgrass color and quality using a 1 to 9 scale (9=ideal, 1=dead, 5=acceptable). Visual quality ratings included an integrated value of plant density, color, growth habit, and uniformity of stand. Beginning with the July 2007 fertilizer application date, reflectance measurements were collected with a handheld reflectance meter (Field Scout® CM-1000 chlorophyll meter). Ambient and reflected light sensed by the meter at 700 nm and 840 nm are used to estimate the quantity of chlorophyll in leaves. Indices provided by the reflectance meter have been correlated to chlorophyll concentration in turfgrass (Mangiafico and Guillard, 2005). In 2008, measurements were collected every two weeks beginning 2 WAT. Five measurements per plot were taken in a systematic grid pattern, using the four corners and center portion. The five measurements were averaged into a single plot measurement reported as a color index. Measurements were taken with the meter facing away from the sun and when canopies were dry. The meter was held approximately 1.5 m from the turf canopy when taking measurements (Mangiafico and Guillard, 2007).

Quantitative analyses consisted of measuring leaf tissue N content, clipping yield (CY) on a dry weight basis, and chlorophyll index readings. Concerning harvest, plots were not mowed for 3 to 5 d prior to observations to provide an ample amount of clippings for analysis. Grass was blown dry using a backpack blower prior to observations. Grass was harvested from each plot using a self-propelled reel-type mower with a 637 mm cutting width at 4, 8, 12, and 16 WAT. Beginning in July 2007, grass was harvested at 4, 8, and 12 WAT from a uniform plot area of 0.96 m^2 representing one pass of the mower to accurately measure clipping weights from a known area. Clippings were bagged and dried at 56°C for approximately 72 h in a laboratory batch oven (GS Blue M Electric, Watertown, WI). Once observations were made, plots were mowed with clippings returned. Occasionally, biosolid granules would be collected in tissue samples and require separation. This was performed using an inclined vibrating deck that utilized gravity for separation (Johnston et al., 2005). Dried clippings were weighed and then ground using a Thomas® Wiley® mini-mill laboratory grinder (Thomas Scientific) with #40 mesh screen (Jiang and Hull, 1998). Ground clippings were stored in 2 oz Whirl-Pak® sample collection bags (NASCO; Modesto, CA) until they could be shipped for total N analysis. Plant tissue samples were analyzed for N concentration via direct combustion-gas chromatography at the University of Nebraska. Data are reported as percentage N on a dry weight basis. Nitrogen recovery, g N m^{-2}, was calculated by multiplying leaf tissue N content and CY. Total clipping yield (TCY) and total nitrogen recovery (TNR) was the addition of their corresponding values at 4, 8, and 12 WAT.

All data were subject to analysis of variance. A PROC GLM split-plot model procedure of SAS v9.1.2 (SAS Institute, 2004) was used to determine significant effects ($P \leq 0.05$). When significant Year x Month or Year x N source interactions existed ($P \leq 0.05$), data was subsequently analyzed separately by year for main effects of Month and N source and their interaction. When Month x N source interactions were not significant ($P \leq 0.05$), data was analyzed to examine main effects of Month and N source. The Replication x Month interaction was used as the error term in tests of hypotheses for the main effect of Month. When significant Month by N source interactions existed, means separation was conducted using Fisher's Protected LSD.

RESULTS AND DISCUSSION

Fairway Study

Leaf tissue N content, clipping yield, and N recovery

Leaf tissue N content analysis of variance indicated a strong Month x Year interaction ($P < 0.0001$) on all four response dates (4, 8, 12, and 16 WAT). When data was analyzed separately by year, significant Month x N source interactions were found at 4, 12, and 16 WAT in 2007 and 8, 12, and 16 WAT in 2008 (Table 1.2).

Data were subsequently analyzed to compare effects of Month within each N source. Davis and Dernoeden (2002) applied urea at 5.0 g N m^{-2} in October, November, December, and the following May (20.0 g N m^{-2} yr^{-1}) to ‘Southshore’ creeping bentgrass. Percentage of leaf tissue N content was recorded one week prior to May fertilization and subsequently in two week intervals to 10 wk after the May treatment. The authors reported a narrow leaf tissue N content range of 4.0 to 4.9% and noted an increase one week following fertilization. Jiang (2005) observed leaf tissue N content values of 3.7, 4.1, 4.4, and 3.9% in July, August, September, and October respectively following fertilization in a mixed stand of Kentucky bluegrass (70%) and fine fescue (30%). A quick release N source was used (32.9% urea-N, 1.2% NH_4^+, 1.9% NO_3^-) to supply N at 2.4 g N m^{-2} each month. In the present study there were relatively few occurrences of leaf tissue N content values within these ranges reported by Davis and Dernoeden (2002) and Jiang (2005). However, all treatments fell within the sufficiency range of 2.4 to 8.3% leaf tissue N content suggested in a survey by Mills and Jones (1996) for healthy creeping bentgrass. In the present study, best turfgrass response with N source application as measured by leaf tissue N content was found during perceived periods of active plant growth, in the spring and fall, where N source treatments were applied in May and September during 2007, respectively. In 2007, May biosolid treatments resulted in significantly higher leaf tissue N content through 16 WAT than most other Months while September biosolid treatments were not significantly different from May through 8 WAT. In 2008, September biosolid treatments were often not significantly different from March treatments, but still resulted in numerically higher leaf tissue N contents. This is evidence that these months were the most effective for Fertilizer treatment applications as measured by transport of N to leaf tissue. No conclusive trends could be drawn among treatments applied in 2008. There was a trend for higher leaf tissue N content from September N source applications, but this was inconclusive due to missing data at 12 WAT.

Miltner et al. (2001) successfully demonstrated the 8 month growing season of the Pacific Northwest with N applications from April through November. In the study April, June, and September were the best suggested times to apply fertilizer N as measured by leaf tissue N content. Also during the study conducted by Miltner et al. (2001) high levels of soil NH_4^+ were found in the spring, a period of increasing soil temperatures and presumed active mineralization. Rapid plant uptake of nutrients from the soil would be expected during this time when plants are growing vigorously (Wilkinson, 1996).

In this study, leaf tissue N contents were usually significantly lower for November N source applications vs. May, July, and September. Unfertilized control plots were seen in the range of leaf tissue N contents suggested by Mills and Jones (1996) during November applications at 8 and 12 WAT in 2008 only. This indicated native soil N and inherent rates of mineralization were unable to supply N to meet these criteria in the late fall. However, plots receiving N treatments were always within this range indicating a positive effect due to late fall N source application. Miltner et al. (2001) found November fertilizer applications to produce the highest concentrations of leaf tissue N contents of perennial ryegrass in the Pacific Northwest, confirming the effectiveness of late fall N fertilization.

Leaf tissue N contents were highest when observed at 4 WAT following N source fertilization in March, May, July, and September of both years (Table 1.3). Blume et al. (2009) noted similar effects where fertilization with biosolid and other organic-N sources produced an immediate increase in leaf tissue N content. Fertilization with AmS and PCSCU N sources appeared to result in higher leaf tissue N content compared with biosolids. These N sources contained more readily available N than biosolid N source treatments. Soundgro treatments were generally not significantly different from Milorganite treatments (P=0.05). Both N sources are products of the same sewage sludge treatment process, which has been shown by Cogger et al. (2004) to affect plant N availability. Unfertilized control plots were on occasion below sufficiency standard levels defined for creeping bentgrass by Mills and Jones (1996) from November to May illustrating the need for N fertilization during late fall. Mineralization appeared to be occurring to some extent when values of unfertilized control plots were compared to biosolid fertilized plots for November applications. Plots treated with Soundgro and Milorganite consistently resulted in significantly higher leaf tissue N contents vs. the unfertilized controls (data not shown).

Clipping yield (CY) analysis of variance indicated Month x Year interactions (P=0.01) 4, 8, and 12 WAT. There were weak Month x N source interactions found in

2007 only when data was analyzed by year (Table 1.4). Main effects of Month and N source treatments are presented for both years.

Total clipping yield was significantly higher for September applications in 2007 and May applications in 2008 compared to all other Months with complete clipping data 4, 8, and 12 WAT (Table 1.5). This was reflective of the typical growth pattern associated with cool-season turfgrasses. While high CY itself may not be a desirable characteristic, it may be considered an overall measure of plant vitality (Mangiafico and Guillard, 2005). Leaf tissue N contents indicated May and September were the most effective times to fertilize (Table 1.3). Wilkinson (1996) noted that roots and leaves are actively extending at rapid rates in the spring. Miltner et al. (2001) found tissue N and soil inorganic N to be higher during spring and fall months compared to summer months, which could account for the increased top growth observed in May and September, and lower growth observed in July. Wilkinson (1996) indicated increasing air temperatures during the summer may cause root and leaf growth to slow. Leaves appeared to be actively extending in the spring. Top growth as measured by CY for March was not significantly different from May at 12 WAT in 2008. Miltner et al. (2001) concluded that high N uptake may not result in high leaf tissue N content if leaf growth rates are high. March applications may be as effective as May applications as evidenced by clipping yield and a lack of significant differences in leaf tissue N content for most sampling dates in 2008 (Table 1.3).

An elevated response in CY was observed with all N source treatments except Milorganite at 4 WAT in 2008 (Table 1.5). Three of four N source treatments resulted in significantly higher CY vs. unfertilized control, while this response declined at 8 and 12

WAT. The effect was more pronounced with the AmS and PCSCU treatments, which resulted in significantly higher CY at 4 (AmS and PCSCU) and 8 (AmS only) WAT vs. biosolids. This was presumably due to the soluble N components contained in these fertilizers (Table 1.1). Starr and DeRoo (1981) found N dry matter accumulation to be rapid approximately 3 wk following application of ^{15}N-labeled AmS. Blume et al. (2009) found natural fertilizer products blended with urea produced an immediate increase in CY compared to other natural organic N sources due to the soluble urea-N component.

Total CY resulting from N source treatments was calculated from July, September, and November applications in 2007, and May and July applications in 2008 due to incomplete data sets (Table 1.5). Clipping yield was generally lower from biosolid fertilization compared to AmS and PCSCU, though this was not always statistically significant, especially for biosolids vs. PCSCU. Total CY reflected less turfgrass response to biosolid fertilization vs. AmS in 2008. These results seemed to correspond with lower leaf tissue N content associated with biosolid N sources. Since only main effects on CY were assessed, application timing of individual fertilizers could not be associated with this result, though low rates of mineralization would be expected during the late fall and early spring months lending preference to less temperature-dependent N sources. It is likely that less biosolid N was available to turfgrass as compared to the AmS N source due to complex forms of recalcitrant N. Cogger et al. (2004) found plant available N to average 37 ± 5% of total biosolid N during the first year of application. The effect was not necessarily negative as lower CY illustrates less need for frequent mowing provided quality can be sustained. No significant difference was found between AmS and PCSCU as measured by CY (except at 4 WAT in 2008) or leaf tissue N content. Similarly, the Milorganite and Soundgro treatments were not significantly different from one another.

Nitrogen recovery plus TNR analysis of variance indicated Month x Year interactions (*P*=0.01) on all three response dates. Month x N source interactions were found in 2007 at 4 and 8 WAT, and TNR (*P*=0.05), and also in 2008 for TNR (*P*=0.20) when data was analyzed by year (Table 1.6). Main effects of Month and N source treatments are presented for both years.

It should be noted that N recovery values only provide a brief 'snapshot' in time. Because clippings were returned between harvests, this value only provided an N recovery value since the previous mowing. In general, highest N recoveries were obtained from September and May applications (Table 1.7). These results seemed to directly correspond with dry CY. Air and soil temperatures were presumed to have a large impact on these results. Air temperatures monitored during this study are presented in Fig. 1.1. Miltner et al. (2001) observed high soil NH_4^+ levels in the spring and fall and presumed this effect to be associated with fluctuating soil temperatures and active mineralization. Nutrient availability was probably influenced in much the same manner during this study. High CY that were found following May and September applications reflected a period of increased plant growth, typical of cool-season turfgrass which resulted in increased nutrient uptake. Leaf tissue N contents from fertilized vs. unfertilized plots indicated a significant uptake of N for all N source treatments. Total N recovery for March, July, and November applications could not be statistically compared due to missing data points. However, there appeared to be a trend for lower N recovery associated with November applications as evidenced by lower N recoveries observed at 8

WAT in 2007 and 12 WAT in 2008. Cooling air temperatures resulted in less top growth, while microbial activity was presumed to slow as seen with decreased leaf tissue N contents in biosolid vs. AmS and PCSCU fertilized plots. Considering this, AmS and PCSCU are probably better choices for late fall fertilization.

An elevated response in N recovery was observed with all N source treatments at 4 WAT in 2008 (Table 1.7). Three of four N source treatments resulted in significantly higher N recovery vs. unfertilized control at 4 WAT, while this response declined at 8 WAT. Also in 2008, highest N recoveries were obtained with the AmS and PCSCU treatments following fertilization at 4 WAT. This corresponded to results found with leaf tissue N content and dry CY. Other studies have demonstrated the immediate response found with soluble-N applications (Starr and DeRoo, 1981; Blume et al., 2009). Evidence suggests that a portion of the total N in biosolids may rapidly mineralize. Muchovej and Rechcigl (1998) applied heat-dried biosolids to forage grass in Florida on a single date in the spring. The largest amount of N recovery was found on the first harvest (35 d), which suggested that most of the biosolids N mineralized soon after application. The more pronounced effect from AmS and PCSCU N sources was presumably due to higher amounts of plant available N contained in these products.

While TNR was a combination of N recovery 4, 8, and 12 WAT, these values were only calculated for July, September, and November applications in 2007, and May and July applications in 2008 due to missed clipping collections because of weather, thus not taking into account March (Table 1.7). Generally, there was less turfgrass response to biosolid treatments vs. PCSCU as measured by N recovery though these effects were not usually statistically significant. Significantly lower TNR was found with applications of Milorganite vs. AmS in 2007 while in 2008 Soundgro applications resulted in significantly lower TNR vs. AmS. A numerically lower TNR was observed with biosolid applications vs. PCSCU in 2007 including observations at 8 and 12 WAT, and 8 WAT and TNR in 2008. In fact, there was over a 20% increase in TNR with PCSCU vs. biosolid applications and 50% with AmS vs. biosolids. A lack of statistical difference was probably from high variability due to missing Month treatment data and thus turfgrass response to biosolid fertilization vs. AmS and PCSCU appeared less as measured by N recovery. Lowest N recovery due to biosolid fertilization was also noted by Hummel and Waddington (1981), Kiemnec et al. (1987), and Cogger et al. (2001). Only a portion of N from the total biosolid N becomes available during the first year of application (Cogger et al., 2004). Nitrogen recovery from Milorganite and Soundgro treatments was never significantly different.

Quality and color ratings, chlorophyll meter index readings

Quality rating analysis of variance indicated Month x Year interactions (P=0.01) on three response dates: 4, 12, and 16 WAT, and significant N source x Year interactions at 4 and 8 WAT (P=0.05). There were significant Month x N source interactions on 4 and 8 WAT in 2008 only when data was analyzed separately by year (Table 1.8). Main effects of Month and N source treatments are presented for both years.

N source treatments applied in March, May, July, and September generally maintained acceptable quality (≥5) through 16 WAT (Table 1.9). No decrease in turfgrass quality was found during the summer months of late June, July, and August as noted by Wilkinson (1996). November applications usually had significantly lower quality ratings than other Month treatments. Turfgrass quality following November N source applications usually resulted in unacceptable ratings (<5), which corresponded to decreased leaf tissue N content, CY, and N recovery. In most studies of late fall N use, acceptable quality ratings have been observed. However, most of these studies used higher annual N rates than the present study. Miltner et al. (2005) found N increasing from 9.8 to 29.4 g N m^{-2} yr^{-1} resulted in a stepwise increase in response as measured by visual quality. Acceptable quality ratings were found in another study by Miltner et al. (2004) at Puyallup, WA. Ammonium sulfate and PCSCU applied in November at 7.4 g N m^{-2} resulted in above acceptable quality ratings through March.

Significant differences in quality ratings among N source treatments were attributed to N availability associated with each treatment source. Ammonium sulfate and PCSCU generally resulted in higher quality ratings than biosolid N sources, though not always statistically significant. Past studies have indicated higher quality ratings associated with synthetic and synthetic-organic N sources (Miltner et al., 2005; Blume et al., 2009). Generally all N source treatments improved quality over unfertilized control plots through 16 WAT. Unacceptable quality ratings of unfertilized control plots illustrate the need for N fertilization in turfgrass culture. Biosolid N sources and the PCSCU treatment were usually not significantly different (P=0.05). Less N was available to the turf when fertilized with biosolids. While turfgrass response was generally increased with the PCSCU treatment as evidenced by N recovery, biosolid N recovery illustrated less available N was needed to maintain acceptable quality turf. Similar to results from N recovery, all N source treatments produced an immediate response 4 WAT while AmS and PCSCU resulted in the largest effect.

Color rating analysis of variance did not indicate any significant Month x Year interactions and only two Month x N source interactions (*P*=0.05). Data for 2007 and 2008 were subsequently combined and analyzed for main effects of Month and N source and their interactions. Significant Month x N source interactions were observed at 4, 8, and 16 WAT (*P*=0.05) (Table 1.10).

Extending plant color response is a highly desirable attribute to an N fertilization program. Month of application was found to significantly affect residual color response with biosolid N sources (*P*=0.05). May applications produced the longest residual color response from fertilization, resulting in acceptable ratings through 16 WAT with all N sources (Table 1.11). July and September applications typically resulted in above acceptable ratings through 12 WAT, though these ratings were usually not significantly different from May applications.

A higher initial plant response to AmS and PCSCU fertilization was observed at 4 WAT with visual color ratings. This response was noted earlier in terms of N recovery. Higher N availability associated with AmS and PCSCU N sources presumably increased this response. This same trend was not observed with biosolid N sources. Highest visual color ratings were most often not observed at 4 WAT, unlike N recovery. However, above acceptable ratings due to biosolid N source applications indicate less available N is needed to produce acceptable colored turf. Hummel and Waddington (1981) found color ratings to improve with the use of soluble N sources. A similar effect was found in the current study. Turfgrass responded with above acceptable color ratings through 16 WAT when AmS was applied in July and November and PCSCU was applied in September and November as compared to Soundgro treated plots during these times. Biosolid N sources generally resulted in acceptable color ratings (≥5) only through 12 WAT, except when applied in May (2007 and 2008) and July (2007).

Biosolid N sources were most effective during presumed times of active mineralization from May to November. Miltner et al. (2001) found high soil NH_4^+ in the spring and fall in the same turfgrass research area. Biosolid N sources were not effective in producing acceptable color response when applied in November. Leaf tissue N content and N recovery measurements indicated some N uptake following this application, but apparently rates of N mineralization were not sufficient to produce acceptable turfgrass color. Unfertilized control plots resulted in below acceptable visual color ratings on every rating date, illustrating the importance of N fertilization in turfgrass culture.

Chlorophyll index analysis of variance indicated significant Month x Year interactions at 12 and 16 WAT ($P<0.0001$) and significant N source x Year interactions at 4, 8, and 12 WAT ($P=0.001$). When data was analyzed separately by year, significant Month x N source interactions were found at 4, 8, and 16 WAT ($P=0.01$) in 2007 (Table 1.12). There were significant Month x N source interactions at 10, 12, 14, and 16 WAT ($P=0.05$) in 2008 (Table 1.13).

Reflectance meter measurements have been shown to directly relate to chlorophyll concentration (Mangiafico and Guillard, 2005), thereby corresponding to greenness of the turf canopy. Turfgrass color as measured objectively with the Spectrum CM1000 chlorophyll meter generally indicated higher chlorophyll indices for fertilized vs. unfertilized control plots during all Months of application (Table 1.14; 1.15). It appeared that less color response could be expected when air temperatures were warm from May to November due to limited significant differences between fertilized plots.

Those significant differences that did exist among N sources were most apparent immediately after fertilizer application in May, July, and September. In most cases turf response was generally highest 2 and 4 WAT. The use of AmS and PCSCU N sources improved this response, while biosolid N sources resulted in lighter color turf (lower chlorophyll index) presumably due to lower N availability.

Nitrogen source was also found to effect chlorophyll content due to fertilization in March and November (Table 1.14; 1.15). Higher chlorophyll indices were found in plots fertilized with AmS and PCSCU during these Months in 2007. November 2008 applications yielded fewer significant differences between AmS and PCSCU, and biosolid N sources (8 to 14 WAT) though numerically these N sources were still higher than biosolid N sources. Visual color ratings indicated an unacceptable response when biosolid N sources were applied in November. The use of AmS and PCSCU N sources were found to improve turfgrass color and chlorophyll (only significant in 2007) during late fall applications.

Home Lawn Study

Leaf tissue N content, clipping yield, and N recovery

Leaf tissue N content analysis of variance indicated significant Month x Year interactions on all observation dates (*P* < 0.0001) and significant N Source x Year interactions 4 WAT (P < 0.0001). When years were analyzed separately, significant Month x N source interactions occurred on all response dates (*P*=0.01) in 2007. In 2008 these interactions were found 4, 12, and 16 WAT (*P*=0.05) (Table 1.16).

Nitrogen source treatments usually resulted in significantly higher leaf tissue N contents in fertilized vs. unfertilized plots during all Months of application through 16 WAT (Table 1.17). This illustrated the capacity for effective turfgrass fertilizer N use in the early spring and late fall. Values in 2007 were generally lower than 2008. A study conducted by Miltner et al. (2001) concluded that April, June, and September were the most effective times to apply fertilizer to turfgrass as measured by leaf tissue N content in the Pacific Northwest. May, August, September, and November were also found to be effective times to fertilize, resulting in leaf tissue N contents from 3.9 to 5.1%, but as high as 6.1% for fertilized perennial ryegrass turf. Similarly, Mills and Jones (1996) suggested leaf tissue N contents for perennial ryegrass from 3.3 to 5.1%. In the current study, N source treatments applied in May, July, September, and November produced leaf tissue N contents within the range suggested by Mills and Jones (1996) and that found by Miltner et al. (2001). This is evidence these months were effective times to fertilize as measured by transport of N to leaf tissue. Higher leaf tissue N contents were observed with November N source treatments vs. unfertilized control indicating N uptake and/or transport was still occurring in the late fall. Miltner et al. (2001) found similar results with a single urea application (4.9 g N m^{-2}) applied in November at the same research site. Effective late fall applied N was also observed by Miltner et al. (1996) when 36% of ^{15}N labeled urea was recovered in Kentucky bluegrass clippings 18 d after application in November. In the current study, turfgrass appeared to respond to a lesser extent in March as indicated by leaf tissue N content. Values observed during this time (2007) often fell below those values established by Mills and Jones (1996).

During 2007 and 2008 leaf tissue N content observations, biosolid N fertilizers were usually not significantly different. Both biosolid products originate from similar sewage sludge treatment processes: anaerobic digestion and heat-drying. Different treatment processes have been found by Cogger et al. (2004) to effect plant available N during the first year of biosolid application to tall fescue (*Festuca arundinacea* Schreb.).

In most cases, turf response to biosolids and AmS and PCSCU N sources was not significantly different, unlike results observed with the FW study. Biosolid N fertilization rates were increased by 50% in this study. Some studies have indicated otherwise. Bushoven and Hull (2005) found that at higher external NO_3^- concentrations, leaf extractable NO_3^- was higher in perennial ryegrass turf. This effect could be expected with the AmS vs. biosolid N sources due to their solubility. However, this was not the case. Native soil N and inherent rates of mineralization may have supplied ample amounts of plant available N as this soil contained over 7% organic matter (Appendix Table III). In fact, a residual effect was noted in biosolid N fertilized plots in 2008. This effect was seen during May and July applications with significantly higher leaf tissue N contents associated with biosolid N fertilized plots, possibly due to recalcitrant N from previous biosolid N applications becoming available. It is well known that biosolid N is not completely plant available during the first year of application. Cogger et al. (2004) concluded that plant available N averaged 37±5% the first year and 13±2% the second year for nonlagoon biosolids (includes Milorganite and Soundgro). Turf growth was maintained by native soil N and inherent rates of mineralization in unfertilized control plots. Leaf tissue N contents increased from May to November overlapping with levels suggested by Mills and Jones (1996), which illustrated the soil's capacity for mineralization during late fall.

Clipping yield analysis of variance indicated significant Month x Year interactions on all observation dates ($P < 0.0001$). When years were analyzed separately, Month x N source interactions were observed at 4 WAT and for TCY in 2007 (P=0.01) and 4 and 12 WAT in 2008 (P=0.05) (Table 1.18).

Clipping yield was usually higher at 4 WAT with all N source treatments (Table 1.19). All N sources contained a portion of water soluble N that would have been quickly available for plant uptake (Table 1.1). Muchovej and Rechcigl (1998) applied biosolids to a Florida forage grass at 0, 2.5, 5.0, 10.0, 20.0, 40.0, and 80.0 g N m^{-2}. Rapid N recovery was observed at 35 days after application. In the current study, no rapid initial response was noted for leaf tissue N content. The magnitude of this effect may have been too small to be noted using methods described in this study, or there was possibly no effect. Native soil N may have swamped the effects of N sources. Miltner et al. (2001) indicated that high rates of N uptake might not result in high leaf tissue N content if dilution occurs due to rapid growth. In either case, highest CY was noted 4 WAT, similar to results found by Starr and DeRoo (1981) who noted rapid dry matter accumulation approximately 3 wk after fertilizer application.

There were few significant differences between N source treatments in CY exhibited by turfgrass. Dry CY production was similar between biosolid N fertilized turf and AmS and PCSCU N fertilized turf. In some instances, significantly higher CY was observed in Soundgro fertilized plots vs. Milorganite and PCSCU fertilized plots. This effect was also observed with November 2007 applications where cooling soil temperatures would be presumed to slow mineralization. Similar results were also observed in November 2008 applications, though only numerical differences among treatments existed. Biosolid N application rates were increased 1.5x beginning with the July 2007 applications to account for decreased first year N availability associated with these products. A lack of significant differences in CY observed between N source treatments justifies the higher application rates. This lack of significant differences could also be explained by native soil N and inherent rates of N mineralization. The Puyallup fine sandy loam contained greater than 7% OM and may have supplied ample amounts of plant available N, as noted above, and could have masked any effects of N source applications. Leaf tissue N content was always above 3.5% for unfertilized control plots, previously noted by Miltner et al. (2001) to be adequate, and that native soil N supplied minimum levels of N to support turfgrass growth. Turfgrass had limited response to late fall applications of biosolid N sources in the FW study as measured by leaf tissue N content, CY, and subsequent N recovery.

Clipping yield is often used by turf managers as an indicator of N sufficiency. Spring and early summer consistently produced the greatest amounts of top growth corresponding to the growth cycle of cool-season turfgrass (Wilkinson, 1996). Total CY appeared greatest when N source treatments were applied in May and July 2008 (not statistically significant) (Table 1.19). High CY may not be viewed as desirable because of increased mowing frequency, but is a good indicator of plant vitality (Mangiafico and Guillard, 2005). November applied N sources appeared to result in lower CY than other months. However, leaf tissue N contents appeared similar to July and September not corresponding to the decrease observed with CY. This was probably an opposite effect to that discussed by Miltner et al. (2001), where increased N uptake may not result in increased leaf tissue N content if rapid growth occurs. Here lower growth rates may have caused a higher concentration in leaf tissue N content. Similar results were found by Ledeboer and Skogley (1973), where spring and summer applied N caused increased top growth vs. November N applications. November fertilized plots resulted in significantly higher CY than unfertilized control plots in 2007 illustrating the capacity for effective fertilizer N use in the late fall. March and September CY appeared intermediate to May and July, and November applications. In most cases, fertilized plots resulted in significantly higher CY vs. unfertilized control plots.

Nitrogen recovery plus TNR analysis of variance indicated significant Month x Year interactions at 4, 8, and 12 WAT (P=0.05), and significant N source x Year interactions at 4 WAT (P=0.05). When years were analyzed separately, significant Month x N source interactions were observed 4 WAT and TNR in 2007 (P=0.05), and 4 and 12 WAT in 2008 (P=0.10) (Table 1.20).

Total N recovery from Soundgro was usually not significantly different from AmS and Milorganite applications (Table 1.21). In some instances, more N was recovered with Soundgro vs. PCSCU fertilized plots. July and November 2007 applications resulted in significantly higher TNR with Soundgro vs. PCSCU fertilized plots and numerically higher N recovery in March (12 WAT only), May (TNR), July (TNR), and November (8 WAT only) 2008. This justified the higher rates of N applied with the biosolid N sources. Some studies have indicated less N recovery with the use of biosolid N vs. synthetic N fertilizers (Moberg et al., 1970; Hummel and Waddington, 1981; Cogger et al., 2001) due to decreased N availability. This was not the case here.

Native soil N and inherent rates of mineralization could have affected N uptake and subsequent N recovery of all N source treated plots. Turfgrass responded similarly to Milorganite and Soundgro treatments. There was usually no significant difference in turfgrass response associated with these N sources as measured by leaf tissue N content, CY, and N recovery. However, greatest periods of N recovery seemed to occur immediately after fertilization, 4 WAT. This effect has been noted earlier in the FW study as well as CY seen with this study. Several studies have noted an immediate turfgrass response to fertilization (Starr and DeRoo, 1981; Muchovej and Rechcigl, 1998; Blume et al., 2009). Rapid biosolid N mineralization, as suggested by Muchovej and Rechcigl (1998), and the proportions of water soluble N contained in these N sources probably played roles in this effect.

Nitrogen recovery appeared higher for N sources applied in May and July (Table 1.21), which corresponded to CY. Turfgrass managers could expect to maximize fertilizer use efficiency when applications are made during these months. Leaf tissue N content proved to be a less reliable indicator of plant growth (Hummel and Waddington, 1981; Miltner et al., 2001; Mangiafico and Guillard, 2007). May applications appeared to exhibit lower leaf tissue N contents than July, September, and November applications (Table 1.17), but increased top growth (Table 1.19). Rapid growth and N uptake resulted in low leaf tissue N contents due to dilution. Turfgrass managers should be cautious about overstimulation of top growth during the spring. Stored carbohydrates can become depleted resulting in increased susceptibility to disease and delayed summer dormancy recovery in cool season turfgrasses (Zanoni et al., 1969). Lowest N recovery was associated with late fall N application. Turfgrass growth at this time was reduced, while leaf tissue N contents were high. Miltner et al. (2001) found inorganic soil N to be highest during this period at Puyallup, WA. Though soil inorganic N was not measured in this study, it would appear plant growth could not keep pace with mineralization. No significant differences among the biosolid N and AmS and PCSCU N sources applied in November presumably indicate active mineralization. Significantly higher N recovery in November fertilized vs. non-fertilized plots demonstrates the capability of N uptake and utilization in the cooler weather of the late fall by turfgrass. Turfgrass managers should be aware of dynamic N pools and how this would impact N fertilization programs.

Quality and color ratings, chlorophyll meter index readings

Quality rating analysis of variance indicated significant Month x Year interactions on all observation dates (P=0.01), and significant N source x Year interactions 4 and 16 WAT (P=0.01). When years were analyzed separately, significant Month x N source interactions were observed 4, 8, and 16 WAT in 2007, and 12 WAT in 2008 (Table 1.22). Main effects of Month and N source treatments are presented for both years.

Throughout the two years of the experiment, May was the only Month of application that resulted in above acceptable quality ratings (≥5.0) through 16 WAT (Table 1.23). In 2008, May applications were significantly higher than all other Months 8 and 12 WAT, and in most cases numerically higher than other Month treatments. May also appeared to result in increased N recovery. Blume et al. (2009) observed above acceptable quality ratings for spring applied fertilizer, including biosolids. In Blume et al.'s study, three N sources were applied at 14.6 g N m^{-2} yr^{-1} beginning in May, which resulted in above acceptable quality ratings 20 wk after the initial treatment. In the current study, March and July applications were often not significantly different from

May. However, quality was observed below acceptable in 2008 12 WAT for March and 16 WAT for July applications. Sustained turf quality is a desirable attribute of any N program. Spring N applications resulted in the most sustained acceptable turfgrass quality ratings.

Turf growth appeared to slow during fall months, as evidenced by lower clipping yields in September and November. Air temperatures decreased from September to January (Fig. 1.1) and probably affected turfgrass growth. Quality ratings for September and November N source applications were usually significantly lower than March, May, and July applications in 2007. Quality ratings for September 2008 N source applications were observed significantly higher than November 8 WAT. Quality was observed above acceptable 4 of 6 observations for September applications and 3 of 6 for November applications. In most studies of late fall N use, acceptable quality has been observed. Miltner et al. (2005) achieved acceptable quality when N was applied at 196 and 294 g N m^{-2} yr^{-1} on perennial ryegrass during fall (September, October, and November) and winter months (December, January, and February). Acceptable winter turfgrass quality was achieved during this study, as evidenced by acceptable ratings during November applications 16 WAT in 2007 and 2008.

In most cases, unfertilized control plots resulted in significantly lower turfgrass quality than fertilized plots, often below acceptable. This illustrates the importance of N in turfgrass culture. A sustained turf response was observed with biosolid N vs. AmS. Biosolid N sources maintained above acceptable quality through 16 WAT in 2007 and 2008 (Table 1.23), while AmS resulted in marginally unacceptable ratings 12 and 16 WAT in 2008. Biosolid N sources resulted in significantly lower quality than AmS and

PCSCU N sources 4 WAT in 2007. However, there was no significant difference in quality ratings between these N sources a majority of the time. Miltner et al. (2005) found higher turfgrass quality when turf was fertilized with synthetic N vs. organic N sources. This was attributed to lower availability of N due to recalcitrant organic forms contained in the organic sources. A similar effect was noted in the FW portion of this study, but was not observed in the current HL study probably due to increased biosolid N rates. However, Davis and Dernoeden (2002) found turf treated with organic fertilizers to be consistently similar or higher than turf fertilized with synthetic N sources, concurrent with results found in the current study.

Color rating analysis of variance indicated significant N source x Year interactions 12 and 16 WAT ($P=0.05$). Data for 2007 and 2008 were subsequently combined and analyzed for main effects of Month and N source and their interactions. There were significant Month x N source interactions on all observation dates ($P=0.05$) (Table 1.24).

Turfgrass response to Treatment effects resulted in more acceptable observations for visual color than quality ratings (Table 1.25). This indicates that an acceptable green canopy may not exhibit acceptable quality. In most cases, acceptable color ratings (≥5) were found with all N sources through 16 WAT during all Month applications. Despite generally lower N conc. in leaf tissue, May applications consistently resulted in significantly higher color ratings across N source treatments, though were sometimes similar to other Month applications. This result was also noted in visual quality ratings above. Mangiafico and Guillard (2005) observed highest color values in April and May when conditions were ideal for cool-season turfgrass growth. Unfertilized control plots were observed above acceptable on 2 of 4 and 3 of 4 dates in May and July, respectively, indicating soil N and inherent rates of mineralization were adequate for producing acceptable turf color.

Biosolid N sources provided above acceptable visual color response in March, July, September, and November through 16 WAT. Unfertilized control plots were only observed above acceptable at one date in September and November, indicating that biosolid N sources were effective during winter months. The AmS and PCSCU N sources resulted in above acceptable color ratings through 16 WAT when applied in September and November, with two exceptions. While plant growth appeared to slow in November, as evidenced by clipping yields, acceptable color was still maintained.

Chlorophyll index analysis of variance indicated significant Year x Month interactions 8, 12, and 16 WAT ($P < 0.0001$), and significant Year x N source interactions 4, 12, and 16 WAT ($P=0.01$). When data was analyzed separately by Year, significant Month x N source interactions were observed 4 and 16 WAT in 2007 (Table 1.26), and 2, 8, and 14 WAT in 2008 (Table 1.27). Main effects of Month and N source treatments are presented for both years.

While N sources applied in May resulted in significantly higher visual turfgrass color ratings (Table 1.25), chlorophyll indices indicated otherwise. May applications tended to result in significantly lower indices compared to July and September applications in 2008 (Table 1.29). Indices from May applications appeared to correspond to lower leaf tissue N contents, as observed above. Guillard and Mangiafico (2007) noted that when turf is actively growing smaller amounts of stored N may be found in leaf tissue.

At five dates of observation, July applications resulted in significantly higher chlorophyll indices compared to other Month treatments. These appeared to correspond to CY, which were numerically higher during July applications. Mangiafico and Guillard (2005) observed a significant linear relationship between clipping yield measurements and chlorophyll meter readings when measured with the Spectrum CM 1000 hand-held chlorophyll reflectance meter. However, this relationship was not observed in the current study, with May applications. September and November applications each resulted in significantly higher chlorophyll indices than other Months on one of three observations in 2007 and two of seven in 2008. March applications resulted in significantly higher indices vs. May applications on three of four observation dates.

Chlorophyll indices indicated a greener canopy on fertilized vs. unfertilized control plots at all observations in 2007 (Table 1.28), and 2 to 6 WAT in 2008 (Table 1.29). Highest observed indices occurred 4 WAT in 2007 and 2 WAT in 2008. This appeared to correspond to a similar effect observed with CY and N recovery, presumably due to soluble N components contained in each N source (Table 1.1). Milorganite and Soundgro N sources were never observed significantly different. Biosolid N sources generally produced a similar turfgrass response to AmS and PCSCU. However, in 2007 indices from Soundgro fertilized plots were significantly higher than AmS and PCSCU 8, 12, and 16 (PCSCU only) WAT, and 12 WAT in 2008.

CONCLUSIONS

Turfgrass response as measured by leaf tissue N contents, CY, N recovery, color and quality ratings, and chlorophyll meter index readings was affected by N source. In most instances limited N availability of complex N forms associated with biosolid N sources produced overall less turfgrass response than the more soluble, AmS and PCSCU, N sources when applied at equal rates. An initial turf response was found following application of N sources. Once applied, N release can be rapid up to 4 wk after application. Periods of highest leaf tissue N contents, CY and subsequent N recovery, quality and chlorophyll content could be expected during this time. Though positive turfgrass response was found with biosolid fertilization, yearly N rates used in this study would not be reflective of rates found in traditional N management programs.

A strong seasonal turfgrass response was found with biosolid N sources in the FW study. Efficiency of these sources was increased when applications were made corresponding to plant growth cycles and periods of expected active microbiological activity. The Soundgro fertilizer treatment produced results similar to Milorganite. Biosolid N sources were found to be most effective when applied in May, and least effective when applied in November. Decreasing air temperatures and top growth probably resulted in ineffective late fall N use from biosolid fertilization. March, July, and September produced positive intermediate results, increasing turfgrass response as measured by leaf tissue N content, CY, N recovery, and color and quality. The biosolid fertilizer evaluated in this study, Soundgro, presented good potential for use on sand-based turfgrass maintained at fairway height.

Soundgro presented good potential for use on home lawns as well. There was less of a response to N source observed during this study compared to the FW study as measured by leaf tissue N content, CY, and N recovery, as well as visual color and quality. Turfgrass response to fertilized plots was generally better than unfertilized control plots. Soundgro resulted in turfgrass response similar to AmS, PCSCU, and

Milorganite, and in some instances was better. This justified the need for increased rates of biosolid N to produce a similar turfgrass response found with AmS and PCSCU N sources.

There was a seasonal turfgrass response observed among application Months in the HL study. Turfgrass response as measured by CY, N recovery, visual color, and quality appeared best when applied in May. Increasing air temperatures during the period, following the May application, probably increased soil microbial activity. March, July, and September applications also resulted in positive turfgrass response to N sources. Effective late fall N use of Soundgro was noted during this study, unlike the FW study. Soundgro was found to result in comparable N recovery to AmS, as well as acceptable visual color ratings throughout the winter. All N sources would be good choices for late fall fertilization. However, May applications can increase fertilizer efficiency.

Nitrogen availability affects the quality of turfgrass, and is an important factor to consider when selecting N products for turf fertilization. Soundgro was found effective as a turfgrass fertilizer. Turfgrass response to this product was similar to Milorganite. These biosolid N sources supplied N to the turfgrass at reduced rates that resulted in acceptable color and quality, but to a lesser extent than AmS and PCSCU. Turfgrass response to biosolid application can be expected to increase when air temperatures are warm and coincide with plant growth, but is effective as a late fall applied source of N on a perennial ryegrass grown on native soil. Applications should be targeted for May, but turfgrass will respond similarly if applications are made in September. Use of biosolids in turfgrass fertilization is an effective way of recycling nutrients while providing an economic benefit for biosolid producers.

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Table 1.1. Fertilizer N sources.

	Short-Kut 16 with Trikote	Anderson's Turf Fertilizer	SoundGro™	Milorganite® 6-2-0 Classic
Nitrogen (N) %	16%	13%	5%	6%
	6.4% ammoniacal N	13.0% ammoniacal nitrogen	3.5% water insoluble nitrogen	5.25% water insoluble nitrogen
	0.6% water soluble organic N		1.5% water soluble nitrogen	0.75% water soluble nitrogen
	9.0% coated slow release N			
Phosphorus (P) %	0.88	0.88	1.76	0.88
Potassium (K) %	13.2	10.7	0.0	0.0
N: P: K ratio	1 : 0.06 : 0.8	1 : 0.07 : 0.8	1 : 0.40 : 0	1 : 0.15 : 0
Other nutrients	13.5% Sulfur (S), 3.8% Iron (Fe)	18.42% S, 2% Fe, 0.10% Cu, 0.10% Mn, 0.10% Zn	3.0% Ca, 0.90% Mg, 0.55% Fe, 0.05% Zn, 0.0010% Mo	4.0% Fe, 1.2% Ca, 1.0% Cl,
Source materials	polymer coated sulfur coated urea, ammonium phosphate sulfate, postassium sulfate, and ferrous oxides	ammonium phosphate, ammonium sulfate, potassium sulfate, ferric oxide, ferrous sulfate, cupric oxide, cupric sulfate, manganous oxide, manganese sulfate, zinc oxide, and zinc sulfate	Anaerobically digested, heat-dried biosolids	Anaerobically digested, heat-dried biosolids
Manufacturer	J.R. Simplot Company, Lathrop, CA	The Anderson's Lawn Fertilizer Division, Maumee, OH	Pierce County, WA Public Works and Utilities, University Place, WA	Milwaukee Metropolitan Sewerage District, Milwaukee, WI

Table 1.2. Analysis of variance by year for leaf tissue N content of fine fescue/colonial bentgrass fairway turf grown on sand in response to Month and N source treatments.

	2007				2008			
	Weeks after treatment							
	4	8	12	16	4	8	12	16
Month	**	**	**	**	§	*	**	ns†
N source	**	**	**	**	**	**	ns	**
Month*N source	§	ns	*	*	ns	**	**	*

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.
†ns=not significant.

Table 1.3. Percentage of leaf tissue N content as affected by Month of application for five N source treatments applied to a fine fescue/colonial bentgrass fairway turf grown on sand during 2007 and 2008.

		2007				2008			
		Weeks after treatment							
		4	8	12	16	4	8	12	16
Check	March	2.3	2.3	2.8	2.9	3.2	3.1	3.0	2.5
	May	3.0	3.1	3.5	2.7	3.1	3.0	3.4	3.0
	July	3.0	2.0	2.9	2.5	2.9	3.0	4.5	3.1
	September	3.2	2.6	2.3	2.0	3.4	3.4	.	2.7
	November	2.3	2.3	1.9	2.1	.	2.7	2.4	2.3
	LSD ‡	0.6	ns	0.4	0.5	ns	ns	1.2	0.2
AmS	March	3.3	2.9	2.9	3.1	4.2	3.8	3.5	2.8
	May	4.0	3.5	3.8	3.2	4.0	3.0	3.1	3.2
	July	3.8	3.2	3.3	2.7	3.7	3.3	4.3	3.3
	September	4.6	3.6	2.9	2.5	4.3	3.8	.	3.3
	November	2.7	2.9	2.8	3.0	.	3.8	3.2	3.2
	LSD	0.5	0.5	0.6	ns	ns	0.6	0.8	ns
PCSCU	March	3.4	3.0	3.0	3.2	4.3	3.7	3.3	2.8
	May	4.0	3.5	3.8	3.3	4.0	3.2	3.3	3.4
	July	3.8	2.9	3.0	2.5	3.4	3.0	4.1	3.0
	September	4.6	3.6	3.0	2.5	4.1	3.8	.	3.3
	November	3.5	2.9	2.9	3.1	.	4.0	3.3	3.2
	LSD	0.5	0.5	0.6	0.6	0.7	0.5	0.7	ns
Milorganite	March	2.7	2.8	3.2	3.2	3.8	3.6	3.5	3.0
	May	3.7	3.6	3.8	3.4	3.7	3.2	3.3	3.3
	July	3.7	3.1	3.4	2.8	3.3	3.2	4.2	3.1
	September	3.8	3.2	2.7	2.4	3.6	3.6	.	3.2
	November	2.6	2.7	2.4	2.5	.	3.4	2.8	2.7
	LSD	0.6	0.4	0.6	0.6	ns	ns	0.7	ns
Soundgro	March	2.9	2.8	3.2	3.3	3.7	3.5	3.4	3.0
	May	3.6	3.4	3.8	3.3	3.7	3.0	3.1	3.2
	July	3.2	2.8	3.0	2.5	3.0	3.0	4.0	3.0
	September	4.0	3.2	2.8	2.4	3.9	3.8	.	3.3
	November	2.8	2.7	2.4	2.5	.	3.4	2.8	2.7
	LSD	0.7	0.6	0.6	0.6	0.6	0.6	0.7	ns

†ns=not significant.

‡Fisher's protected Least Significant Difference (*P*=0.05).

Table 1.4. Analysis of variance by year for turfgrass clipping yield of fine fescue/colonial bentgrass fairway turf grown on sand in response to Month and N source treatments.

	2007				2008			
	Weeks after treatment							
	4	8	12	Total	4	8	12	Total
Month	ns†	**	ns	§	ns	**	**	**
N source	§	**	ns	§	**	*	ns	§
Month*N source	*	§	ns	§	ns	ns	ns	ns

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.

†ns=not significant.

Table 1.5. Turfgrass clipping yield (g dry matter m^{-2}) as affected by Month of application and N source for a fine fescue/colonial bentgrass fairway turf grown on sand.

	2007				2008			
	Weeks after treatment							
	4	8	12	Total	4	8	12	Total
Month								
March	.§	.	.	.	12.6	.	12.3	.
May	.	16.7	.	.	16.3	12.5	11.0	39.8
July	6.5	10.2	6.4	23.2	14.1	3.8	5.9	23.7
September	10.3	16.5	9.3	36.2	10.9	8.9	.	.
November	10.5	2.4	8.7	21.6	.	6.9	4.0	.
LSD ‡	ns†	4.0	ns	8.0	ns	2.0	2.6	7.3
N Source								
Check	4.6	8.0	5.4	18.4	8.1	6.2	7.2	21.2
AmS	9.7	15.0	9.9	32.8	19.7	9.6	9.4	42.1
PCSCU	9.3	13.7	8.8	30.2	16.4	7.9	8.3	33.8
Milorganite	9.5	11.7	7.6	25.8	10.8	7.3	9.0	29.0
Soundgro	12.5	9.0	9.0	27.7	12.3	9.0	7.6	29.6
LSD	5.2	4.5	ns	10.4	3.3	2.2	ns	11.6

†ns=not significant.

‡Fisher's protected Least Significant Difference (*P*=0.05).

§Data not collected where values are missing.

Table 1.6. Analysis of variance by year for tissue N recovery of fine fescue/colonial bentgrass fairway turf grown on sand in response to Month and N source treatments.

	2007				2008			
	Weeks after treatment							
	4	8	12	Total	4	8	12	Total
Month	§	**	ns†	*	ns	**	§	§
N Source	**	**	ns	**	**	§	ns	ns
Month*N Source	*	§	ns	*	ns	ns	ns	¶

¶, §, *, ** Significantly different at *P*=0.20, 0.10, 0.05, 0.01, respectively.

†ns=not significant

Table 1.7. Nitrogen recovery (g N m^{-2}) in turfgrass leaf tissue as affected by Month of application and N source for a fine fescue/colonial bentgrass fairway turf grown on sand.

	2007				2008			
	Weeks after treatment							
	4	8	12	Total	4	8	12	Total
Month								
March	.§	.	.	.	0.51	.	0.40	.
May	.	0.59	.	.	0.60	0.38	0.37	1.36
July	0.23	0.26	0.21	0.70	0.49	0.13	0.25	0.86
September	0.45	0.57	0.27	1.29	0.44	0.33	.	.
November	0.31	0.06	0.23	0.60	.	0.25	0.12	.
LSD ‡	0.13	0.12	ns†	0.24	ns	0.08	0.12	0.33
N source								
Check	0.13	0.16	0.15	0.42	0.26	0.21	0.25	0.71
AmS	0.39	0.52	0.31	1.15	0.79	0.33	0.33	1.51
PCSCU	0.38	0.47	0.26	1.05	0.66	0.29	0.28	1.21
Milorganite	0.32	0.40	0.22	0.82	0.39	0.24	0.31	1.00
Soundgro	0.42	0.30	0.25	0.88	0.45	0.30	0.25	0.98
LSD	0.17	0.14	ns	0.31	0.14	0.09	ns	0.52

†ns=not significant.

‡Fisher's protected Least Significant Difference (*P*=0.05).

§Data not collected where values are missing.

Table 1.8. Analysis of variance by year for quality ratings of fine fescue/colonial bentgrass fairway turf grown on sand in response to Month and N source treatments.

	2007				2008			
	Weeks after treatment							
	4	8	12	16	4	8	12	16
Month	**	§	**	§	§	ns†	**	**
N source	**	**	**	**	**	**	*	§
Month*N source	ns	ns	ns	ns	**	**	ns	ns

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.

†ns=not significant.

Table 1.9. Main effects of Month and N source treatments on turfgrass quality ratings* following application of fertilizer to a fine fescue/colonial bentgrass fairway turf grown on sand.

	2007				2008			
	Weeks after treatment							
	4	8	12	16	4	8	12	16
Month								
March	5.7	6.3	5.6	.§	5.6	5.7	6.1	4.5
May	6.2	6.6	6.4	.	5.8	5.8	5.7	5.6
July	6.8	5.9	6.1	5.4	6.0	5.7	6.1	5.7
September	6.3	6.2	5.5	5.4	6.5	5.6	.	4.7
November	5.3	.	4.5	4.4	.	4.8	5.1	3.8
LSD ‡	0.4	0.5	0.5	0.4	0.4	ns†	0.5	0.5
N source								
Check	4.8	4.8	4.9	4.4	5.0	4.6	5.1	4.4
AmS	7.1	6.8	6.0	5.6	6.7	6.2	6.1	5.0
PCSCU	6.6	7.0	5.9	5.3	6.1	5.7	5.8	4.9
Milorganite	5.7	6.1	5.6	5.1	5.9	5.4	5.8	5.2
Soundgro	6.2	6.6	5.7	5.0	6.2	5.6	5.8	4.8
LSD	0.4	0.5	0.5	0.5	0.5	0.4	0.6	0.5

*Rating scale: 1-9; with 9 indicating best quality, and 3 acceptable quality.
†ns=not significant.
‡Fisher's protected Least Significant Difference (*P*=0.05).
§Data not collected where values are missing.

Table 1.10. Analysis of variance for 2007 and 2008 color ratings of fine fescue/colonial bentgrass fairway turf grown on sand in response to Month and N source treatments.

	Weeks after treatment			
Source	4	8	12	16
N source	**	**	**	**
Month	**	**	**	**
Year	ns†	§	**	ns
Month*N source	**	*	§	**
Year*N source	ns	ns	*	*
Year*Month	ns	ns	ns	ns
Year*Month*N source	*	ns	ns	§

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.
†ns=not significant.

Table 1.11. Turfgrass color ratings as affected by Month of application for five N source treatments applied to a fine fescue/colonial bentgrass fairway turf grown on sand, mean of 2007 and 2008.

		Weeks after treatment			
		4	8	12	16
Check	March	3.8*	4.8	4.9	4.3
	May	4.4	5.1	4.6	4.5
	July	4.8	4.6	4.6	4.4
	September	4.6	4.0	3.0	3.1
	November	3.0	3.3	3.1	2.8
	LSD ‡	0.8	0.7	1.1	1.1
AmS	March	7.5	6.5	5.9	3.0
	May	6.9	6.4	5.5	5.5
	July	6.6	6.4	5.9	5.6
	September	7.4	7.0	5.8	4.8
	November	5.3	5.8	5.4	5.0
	LSD	0.8	ns†	ns	0.8
PCSCU	March	7.3	6.5	5.9	3.5
	May	6.9	6.4	5.6	5.8
	July	6.5	5.8	5.5	4.9
	September	7.0	6.8	5.8	5.0
	November	5.8	6.0	5.4	5.0
	LSD	0.8	0.7	ns	0.8
Milorganite	March	5.3	5.5	5.6	4.8
	May	5.9	6.5	5.5	5.8
	July	6.5	6.0	5.6	5.3
	September	6.0	5.9	5.0	4.6
	November	3.8	4.8	4.6	4.1
	LSD	0.7	0.8	0.8	0.8
Soundgro	March	5.9	5.8	6.5	3.8
	May	5.8	6.4	5.6	5.3
	July	6.1	5.6	5.6	4.9
	September	6.1	5.6	5.0	4.5
	November	4.5	5.0	4.3	3.8
	LSD	0.7	0.8	0.9	0.8

*Rating scale: 1-9; with 9 indicating darkest green color.
†ns=not significant.
‡Fisher's protected Least Significant Difference (*P*=0.05).

Table 1.12. Analysis of variance for Month and N source effects on turfgrass color index of fine fescue/colonial bentgrass fairway turf grown on sand, 2007.

	Weeks after treatment			
	4	8	12	16
Month	**	*	**	**
N source	**	**	**	**
Month*N source	**	**	ns	**

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.
†ns=not significant

Table 1.13. Analysis of variance for Month and N source effects on turfgrass color index of fine fescue/colonial bentgrass fairway turf grown on sand, 2008.

	Weeks after treatment							
	2	4	6	8	10	12	14	16
Month	**	ns†	ns	**	**	**	*	**
N source	**	**	**	**	**	**	**	ns
Month*N source	§	§	ns	§	*	*	**	**

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.
†ns=not significant.

Table 1.14. Turfgrass color index as affected by five different N sources applied in five different months to a fine fescue/colonial bentgrass fairway turf grown on sand, 2007.

		Weeks after treatment			
		4	8	12	16
May ¶	Check	.	.	.	335§
	AmS	.	.	.	388
	PCSCU	.	.	.	353
	Milorganite	.	.	.	380
	Soundgro	.	.	.	426
	LSD ‡	.	.	.	ns†
July	Check	.	302	306	230
	AmS	.	362	385	279
	PCSCU	.	356	352	259
	Milorganite	.	384	381	289
	Soundgro	.	336	337	257
	LSD	.	ns	ns	ns
September	Check	334	295	196	297
	AmS	564	495	284	368
	PCSCU	540	486	292	321
	Milorganite	432	416	261	327
	Soundgro	424	400	258	312
	LSD	66	62	42	ns
November	Check	190	.	121	151
	AmS	260	.	198	276
	PCSCU	283	.	217	296
	Milorganite	222	.	162	201
	Soundgro	246	.	173	210
	LSD	58	.	23	42

¶Chlorophyll meter index collection did not start until 16 Weeks after treatment in May.
†ns=not significant.
‡Fisher's protected Least Significant Difference (*P*=0.05).
§Index of relative chlorophyll content measured by reflectance of 700 nm and 840 nm light.

Table 1.15. Turfgrass color index as affected by five different N sources applied in five different months to a fine fescue/colonial bentgrass fairway turf grown on sand, 2008.

		Weeks after treatment							
		2	4	6	8	10	12	14	16
March	Check	.	317	.	333	.	251	.	230
	AmS	.	467	.	457	.	301	.	181
	PCSCU	.	449	.	431	.	286	.	222
	Milorganite	.	398	.	402	.	324	.	236
	Soundgro	.	388	.	395	.	299	.	213
	LSD ‡	.	57	.	44	.	32	.	ns†
May	Check	.	288	.	230	.	259	.	499
	AmS	.	384	.	271	.	320	.	467
	PCSCU	.	416	.	285	.	319	.	481
	Milorganite	.	367	.	275	.	332	.	524
	Soundgro	.	374	.	297	.	314	.	490
	LSD	.	35	.	27	.	54	.	ns
July	Check	232§	261	.	246	293	408	319	299
	AmS	356	403	.	301	300	418	314	312
	PCSCU	340	347	.	272	299	388	300	284
	Milorganite	264	333	.	293	301	392	301	292
	Soundgro	266	305	.	268	305	380	302	285
	LSD	23	55	.	ns	ns	ns	ns	ns
September	Check	355	320	268	300	280	.	228	211
	AmS	428	402	335	397	360	.	288	260
	PCSCU	418	388	336	419	361	.	296	264
	Milorganite	377	336	290	353	325	.	274	240
	Soundgro	386	347	312	374	331	.	293	266
	LSD	32	37	23	48	36	.	42	36
November	Check	268	.	268	202	182	157	340	162
	AmS	317	.	317	275	243	216	368	236
	PCSCU	323	.	323	295	262	219	346	249
	Milorganite	280	.	280	246	223	194	357	200
	Soundgro	294	.	294	257	230	192	385	200
	LSD	ns	.	ns	49	37	22	34	34

†ns=not significant.

‡Fisher's protected Least Significant Difference (*P*=0.05).

§Index of relative chlorophyll content measured by reflectance of 700 nm and 840 nm light.

Table 1.16. Analysis of variance by year for Month and N source effects on leaf tissue N content of a mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions

	2007				2008			
	Weeks after treatment							
	4	8	12	16	4	8	12	16
Month	**	**	**	**	**	**	**	**
N source	**	**	**	**	**	**	**	**
Month*N source	**	**	**	**	*	ns†	**	**

*, ** Significantly different at *P*=0.05, 0.01, respectively.
†ns=not significant.

Table 1.17. Percentage of leaf tissue N content as affected by five different N sources applied in five different months to a mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions.

		2007				2008			
		Weeks after treatment							
		4	8	12	16	4	8	12	16
March	Check	2.9	2.8	2.5	2.8	3.9	3.4	3.2	3.2
	AmS	3.7	3.1	2.7	2.5	4.7	3.7	3.2	3.2
	PCSCU	3.6	3.1	2.7	2.6	4.6	3.8	3.2	3.2
	Milorganite	3.1	2.9	2.6	2.7	4.6	3.8	3.2	3.4
	Soundgro	3.2	3.0	2.7	2.7	4.5	3.8	3.2	3.4
	LSD ‡	0.1	0.2	0.1	0.2	0.2	0.2	ns	0.2
May	Check	2.5	2.8	3.7	4.0	3.0	2.9	3.5	4.2
	AmS	3.0	3.1	3.7	4.0	3.5	3.2	3.5	4.0
	PCSCU	3.1	3.0	3.6	3.9	3.5	3.2	3.6	4.1
	Milorganite	2.9	3.0	3.8	4.0	3.6	3.2	3.8	4.3
	Soundgro	2.9	3.1	3.7	4.1	3.6	3.4	3.8	4.3
	LSD	0.1	0.2	ns	ns	0.1	0.2	0.3	0.2
July	Check	3.6	3.7	4.1	3.5	3.6	4.3	4.6	4.7
	AmS	3.8	3.9	4.3	3.7	3.8	4.3	4.6	4.6
	PCSCU	3.8	3.9	4.3	3.7	3.8	4.2	4.7	4.7
	Milorganite	3.9	3.9	4.4	3.7	3.9	4.4	5.1	5.1
	Soundgro	3.8	3.9	4.3	3.8	3.9	4.4	5.0	4.8
	LSD	ns	0.1	0.2	0.1	ns	ns	0.2	0.2
September	Check	4.1	3.7	3.9	3.7	4.3	4.6	.	4.3
	AmS	4.4	3.9	4.3	4.0	4.8	5.0	.	4.6
	PCSCU	4.6	4.0	4.3	4.2	4.8	5.0	.	4.6
	Milorganite	4.6	4.0	4.4	4.1	4.7	4.9	.	4.6
	Soundgro	4.6	4.0	4.4	4.2	5.0	5.1	.	4.6
	LSD	0.1	0.2	0.3	0.3	0.3	0.3	.	ns
November	Check	3.7	3.8	3.8	3.8	.	4.5	4.0	3.8
	AmS	4.6	4.6	4.4	4.5	.	4.9	4.4	4.2
	PCSCU	4.3	4.6	4.4	4.4	.	4.9	4.4	4.2
	Milorganite	4.4	4.6	4.4	4.5	.	4.9	4.5	4.2
	Soundgro	4.4	4.7	4.5	4.5	.	4.8	4.4	4.1
	LSD	0.2	0.2	0.2	0.2	.	ns	0.1	0.1

‡Fisher's protected Least Significant Difference (*P*=0.05).
†ns=not significant.
§Data not collected where values are missing.

Table 1.18. Analysis of variance by year for turfgrass clipping yield of mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions in response to Month and N source treatments.

	2007				2008			
	Weeks after treatment							
	4	8	12	Total	4	8	12	Total
Month	**	**	**	**	**	**	**	ns
N source	**	**	**	**	**	**	**	**
Month*N source	**	ns†	§	**	**	§	*	ns

§, *, ** Significantly different at P=0.10, 0.05, 0.01, respectively.
†ns=not significant.

Table 1.19. Turfgrass clipping yield (g dry matter m^{-2}) as affected by five different N sources applied in five different months to a mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions.

		2007				2008			
		Weeks after treatment							
		4	8	12	Total	4	8	12	Total
March	Check	.§	.	.	.	5.7	.	57.1	.
	AmS	.	.	.	.	20.9	.	60.8	.
	PCSCU	.	.	.	.	20.4	.	52.3	.
	Milorganite	.	.	.	.	17.7	.	63.9	.
	Soundgro	.	.	.	.	20.7	.	61.2	.
	LSD ‡	.	.	.		8.7	.	ns	.
May	Check	.	14.3	.	.	57.9	27.4	18.0	103.3
	AmS	.	25.1	.	.	79.7	47.0	28.4	155.1
	PCSCU	.	23.2	.	.	79.2	40.6	26.4	146.3
	Milorganite	.	23.3	.	.	71.9	49.0	35.2	156.0
	Soundgro	.	27.4	.	.	80.1	46.7	43.3	170.1
	LSD	.	8.9	.	.	14.7	7.8	15.2	29.3
July	Check	20.5	19.3	20.4	60.3	18.2	26.8	41.3	86.3
	AmS	40.2	21.7	28.7	90.6	71.5	34.2	41.1	146.7
	PCSCU	41.9	19.9	21.4	83.2	69.1	32.9	38.3	140.3
	Milorganite	43.8	22.5	32.6	98.9	61.9	35.9	44.0	141.8
	Soundgro	45.2	27.6	33.3	106.1	72.6	37.7	42.4	152.7
	LSD	9.2	ns	11.1	18.7	14.1	ns	ns	26.2
September	Check	15.1	7.1	2.9	25.1	31.6	17.8	.	.
	AmS	51.1	12.4	5.2	68.7	47.7	26.3	.	.
	PCSCU	42.1	8.0	4.7	54.8	43.6	20.6	.	.
	Milorganite	55.1	9.5	4.8	69.4	37.2	21.1	.	.
	Soundgro	46.4	10.9	5.6	63.0	42.0	25.2	.	.
	LSD	10.5	ns	ns	10.9	ns	ns	.	.
November	Check	3.5	1.7	1.1	6.4	.	13.3	5.2	.
	AmS	9.6	5.5	3.3	18.4	.	12.8	3.9	.
	PCSCU	7.5	5.0	3.3	15.9	.	11.7	5.3	.
	Milorganite	6.8	4.5	3.7	14.9	.	12.6	5.0	.
	Soundgro	10.9	6.4	4.2	21.5	.	17.9	4.9	.
	LSD	3.2	1.1	1.8	4.3	.	ns	ns	.

†ns=not significant.

‡Fisher's protected Least Significant Difference (*P*=0.05).

§Data not collected where values are missing.

Table 1.20. Analysis of variance by year for tissue N recovery of mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions in response to Month and N source treatments.

	2007				2008			
.	Weeks after treatment							
	4	8	12	Total	4	8	12	Total
Month	**	**	**	**	**	**	**	§
N source	**	**	**	**	**	**	**	**
Month*N source	**	ns†	§	**	*	ns	§	ns

§, *, ** Significantly different at *P*=0.10, 0.05, 0.01, respectively.

†ns=not significant.

Table 1.21. Nitrogen recovery (g N m^{-2}) in turfgrass leaf tissue as affected by five different N sources applied in five different months to a mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions.

		2007				2008			
		Weeks after treatment							
		4	8	12	Total	4	8	12	Total
March	Check	.§	.	.	.	0.22	.	1.83	.
	AmS	.	.	.	.	0.98	.	1.95	.
	PCSCU	.	.	.	.	0.96	.	1.66	.
	Milorganite	.	.	.	.	0.81	.	2.07	.
	SoundGro	.	.	.	.	0.95	.	1.99	.
	LSD ‡	.	.	.	.	0.44		ns	.
May	Check	.	0.40	.	.	1.76	0.81	0.64	3.21
	AmS	.	0.78	.	.	2.77	1.49	1.00	5.26
	PCSCU	.	0.69	.	.	2.78	1.30	0.95	5.02
	Milorganite	.	0.71	.	.	2.57	1.59	1.33	5.50
	SoundGro	.	0.86	.	.	2.91	1.57	1.68	6.16
	LSD	.	0.31	.	.	0.49	0.28	0.64	1.16
July	Check	0.73	0.72	0.85	2.30	0.67	1.15	1.91	3.73
	AmS	1.51	0.85	1.22	3.58	2.78	1.46	1.90	6.14
	PCSCU	1.58	0.76	0.93	3.28	2.62	1.39	1.78	5.79
	Milorganite	1.71	0.89	1.43	4.02	2.42	1.59	2.24	6.25
	SoundGro	1.74	1.09	1.41	4.24	2.81	1.67	2.13	6.60
	LSD	0.35	ns	0.47	0.73	0.62	ns	ns	1.23
September	Check	0.62	0.27	0.11	1.01	1.35	0.84	.	.
	AmS	2.26	0.49	0.23	2.98	2.29	1.32	.	.
	PCSCU	1.95	0.32	0.20	2.47	2.09	1.03	.	.
	Milorganite	2.54	0.38	0.21	3.14	1.74	1.04	.	.
	SoundGro	2.12	0.44	0.25	2.81	2.11	1.29	.	.
	LSD	0.49	ns	0.10	0.51	0.69	ns	.	.
November	Check	0.13	0.07	0.04	0.24	.	0.61	0.21	.
	AmS	0.44	0.25	0.15	0.84	.	0.63	0.17	.
	PCSCU	0.33	0.23	0.15	0.70	.	0.56	0.23	.
	Milorganite	0.30	0.20	0.16	0.67	.	0.61	0.22	.
	SoundGro	0.48	0.30	0.19	0.97	.	0.88	0.22	.
	LSD	0.15	0.05	0.08	0.21	.	ns	ns	.

‡Fisher's protected Least Significant Difference (*P*=0.05).

†ns=not significant.

§Data not collected where values are missing.

Table 1.22. Analysis of variance by year for quality ratings of mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions in response to Month and N source treatments.

	2007				2008			
	Weeks after treatment							
	4	8	12	16	4	8	12	16
Month	**	§	**	**	§	**	**	ns†
N source	**	**	**	**	**	*	**	ns
Month*N source	**	**	ns	**	ns	§	*	ns

§, *, ** Significantly different at P=0.10, 0.05, 0.01, respectively.
†ns=not significant.

Table 1.23. Main effects of Month and N source treatments on turfgrass quality ratings following application of fertilizer to mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions.

	2007				2008			
	Weeks after treatment							
	4	8	12	16	4	8	12	16
Month								
March	5.2*	6.0	5.5	.§	5.8	5.4	4.8	5.3
May	6.0	5.9	5.6	.	5.8	6.0	6.2	5.4
July	5.8	5.7	.	5.6	6.3	5.5	5.3	4.9
September	.	5.4	4.6	4.4	5.7	5.5	.	5.0
November	5.1	.	4.5	5.0	.	4.5	4.8	5.0
LSD ‡	0.3	0.4	0.4	0.3	0.5	0.4	0.4	ns†
N source								
Check	4.3	5.1	4.4	3.9	4.9	4.9	5.1	5.0
AmS	5.9	5.7	5.1	5.3	6.2	5.5	4.9	4.9
PCSCU	6.3	5.8	4.9	5.2	5.9	5.5	5.2	5.3
Milorganite	5.4	5.8	5.3	5.2	6.1	5.5	5.8	5.2
Soundgro	5.8	6.2	5.3	5.4	6.3	5.5	5.4	5.2
LSD	0.4	0.4	0.4	0.4	0.5	0.4	0.5	ns

*Rating scale: 1-9; with 9 indicating best quality, and 3 acceptable quality.
†ns=not significant.
‡Fisher's protected Least Significant Difference (P=0.05).
§Data not collected where missing.

Table 1.24. Analysis of variance for 2007 and 2008 color ratings of mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions in response to Month and N source treatments.

	Weeks after treatment			
Source	4	8	12	16
N source	**	**	**	**
Month	**	**	**	**
Year	*	ns†	ns	ns
Month*N source	*	**	*	*
Year*N source	**	ns	*	**
Year*Month	**	ns	**	ns
Year*Month*N source	ns	**	ns	ns

*, ** Significantly different at *P*=0.05, 0.01, respectively.
†ns=not significant.

Table 1.25. Turfgrass color ratings as affected by Month of application for five N source treatments applied to mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions, mean of 2007 and 2008.

		Weeks after treatment			
		4	8	12	16
Check	March	4.1*	4.6	4.9	5.0
	May	4.9	4.9	5.6	5.8
	July	5.5	5.1	5.0	4.8
	September	5.0	4.8	4.0	4.8
	November	4.5	5.0	3.8	4.3
	LSD ‡	0.6	ns	0.6	0.9
AmS	March	6.8	5.8	5.1	4.8
	May	6.8	6.6	6.0	5.8
	July	7.0	5.9	5.0	5.3
	September	6.0	5.9	4.5	5.0
	November	6.0	5.3	5.1	6.4
	LSD	ns	0.8	0.5	0.8
PCSCU	March	6.6	5.6	5.3	4.8
	May	6.1	6.3	6.0	6.0
	July	6.9	5.9	6.0	5.5
	September	6.3	5.9	4.8	5.3
	November	6.0	5.5	5.3	6.1
	LSD	ns	ns	0.7	0.9
Milorganite	March	5.9	6.1	6.1	5.8
	May	6.4	7.0	7.0	6.3
	July	6.8	6.5	5.3	5.1
	September	6.5	5.9	5.5	5.1
	November	6.3	4.8	5.4	6.1
	LSD	ns	0.7	0.8	0.9
Soundgro	March	6.0	5.6	5.8	6.0
	May	6.0	7.6	7.1	6.0
	July	7.0	6.1	5.8	5.4
	September	6.5	6.1	5.3	5.1
	November	6.0	5.0	4.9	6.1
	LSD	0.8	0.8	0.9	0.9

*Rating scale: 1-9; with 9 indicating darkest green color.

†ns=not significant.

‡Fisher’s protected Least Significant Difference (*P*=0.05).

Table 1.26. Analysis of variance for Month and N source effects on turfgrass color index of mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions, 2007.

	Weeks after treatment			
	4	8	12	16
Month	**	§	**	**
N source	**	**	**	**
Month*N source	**	ns†	§	**

§, ** Significantly different at *P*=0.10, 0.01, respectively.
†ns=not significant.

Table 1.27. Analysis of variance for Month and N source effects on turfgrass color index of mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions, 2008.

	Weeks after treatment							
	2	4	6	8	10	12	14	16
Month	**	**	**	**	**	**	**	**
N source	**	**	**	§	ns†	**	ns	**
Month*N source	**	ns	ns	**	ns	ns	**	§

§, ** Significantly different at *P*=0.10, 0.01, respectively.
†ns=not significant.

Table 1.28. Turfgrass color index as affected by five different N sources applied in five different months to mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions, 2007.

	Weeks after treatment			
	4	8	12	16
Month				
March	.†	.	.	.
May	.	.	.	499§
July	.	459	562	384
September	663	415	335	.
November	329	.	344	531
LSD ‡	27	16	24	18
N Source				
Check	392	407	341	400
AmS	544	433	420	484
PCSCU	507	435	420	480
Milorganite	524	449	428	488
Soundgro	511	462	459	505
LSD	43	26	31	23

†Data not collected where missing.
‡Fisher's protected Least Significant Difference (*P*=0.05).
§Index of relative chlorophyll content measured by reflectance of 700 nm and 840 nm light.

Table 1.29. Turfgrass color index as affected by five different N sources applied in five different months to mature perennial ryegrass turf grown on a Puyallup fine sandy loam soil maintained under home lawn conditions, 2008.

	Weeks after treatment							
Month	2	4	6	8	10	12	14	16
March	.†	779§	.	468	.	379	.	414
May	.	444	.	414	.	460	.	261
July	588	562	.	575	596	597	471	491
September	531	472	516	726	614	.	409	284
November	683	.	683	244	259	283	222	436
LSD ‡	22	33	20	19	25	22	16	20
N Source								
Check	509	471	556	474	505	417	352	362
AmS	627	589	616	479	479	418	369	367
PCSCU	640	577	614	481	475	409	377	381
Milorganite	601	585	591	496	482	455	369	396
SoundGro	625	599	619	497	507	451	368	381
LSD	28	36	31	19	ns*	25	ns	20

†Data not collected where missing.

*ns=not significant.

‡Fisher's protected Least Significant Difference (*P*=0.05).

§Index of relative chlorophyll content measured by reflectance of 700 nm and 840 nm light.

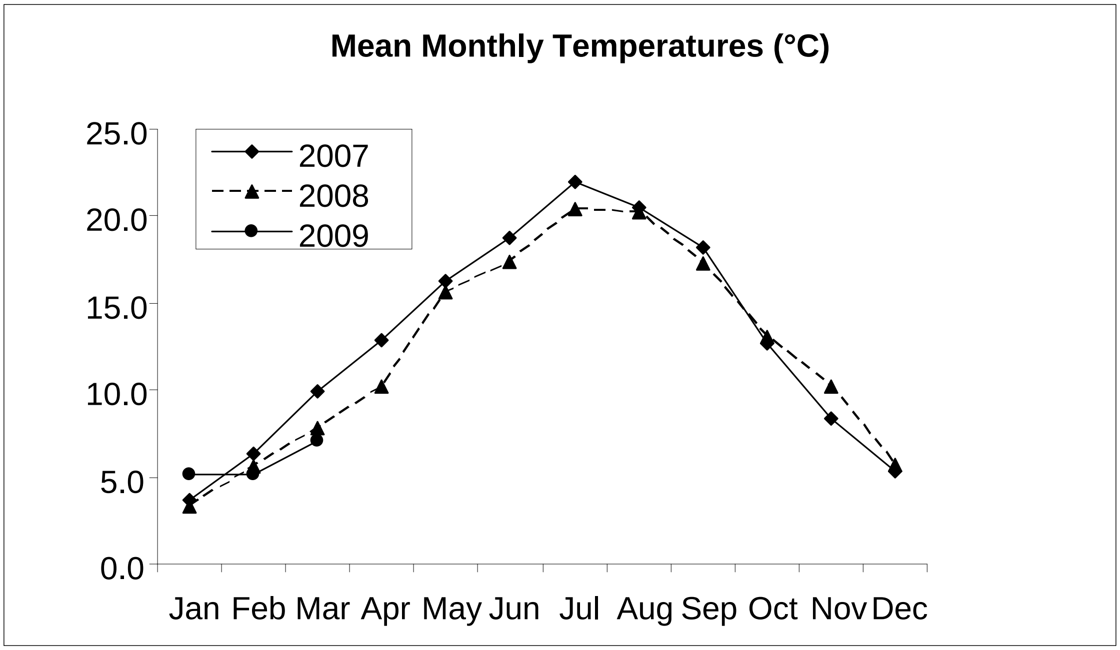

Fig. 1.1. Air temperature at the R. L. Goss Turfgrass Research Facility, Puyallup, WA.

CHAPTER II

INORGANIC N RELEASE OF TWELVE TURFGRASS FERTILIZERS

ABSTRACT

Natural organic fertilizers are becoming more widely used in turfgrass management. Many of these products contain multiple N sources with varying N-release characteristics. A laboratory incubation study was conducted to compare 9 natural organic N fertilizers (each containing one or more of biosolids, feather meal, steamed bone meal, dried poultry manure, nitrate of soda, soybean meal, blood meal, dried poultry waste, alfalfa meal, or seaweed extract). These were compared to three synthetic industry standards: two sources of ammonium sulfate (AmS), a polymer-coated sulfur-coated urea (PCSCU), and an unfertilized control. Samples of Puyallup fine sandy loam were incubated under aerobic conditions amended with N products at 400 mg N kg^{-1} soil. Total N (NH_4+NO_3) was determined 0, 1, 2, 4, 8, 10, 12, and 16 wk after incubation at 22°C. A large fraction of inorganic N was released during the first week of incubation, after which amounts remained similar. Higher amounts of total N were extracted from AmS and PCSCU treated soils. Approximately 73 to 87% of applied N was released with these fertilizers. The data indicated that from 34 to 68% of applied N from other natural organic N sources and 31 to 43% of biosolids N was released during the 16 wk incubation. Biosolids appeared to release N at a lower rate, similar to dried poultry waste alone. An increase in N release between fertilizers was found to correlate to a decrease in their respective C:N ratios (R^2=0.74; *P*=0.0002). Comparing fertilizers based on source materials was not as effective as making comparisons based on C:N ratios.

Abbreviations: AmS, ammonium sulfate; PCSCU, polymer-coated sulfur-coated urea; OM, organic matter; AP, alfalfa pellets; CM, chicken manure; BM, blood meal.

INTRODUCTION

Natural organic fertilizers are becoming more popular every year. Use of these N fertilizers on golf courses and other turf settings has been increasing due to the desire of turfgrass managers to increase their level of environmental stewardship. Benefits of these products include slow-release N (Carrow et al., 1997), low salt indices reducing foliar burn (Noer, 1925; Moberg et al., 1970), and low leaching potential (Easton and Petrovic, 2004). However, relatively little is known of their N release characteristics. This can be a source of ambiguity when trying to provide N efficiently while minimizing environmental pollution.

Application of these N fertilizers requires an understanding of their respective N availability to make environmentally sound and efficient applications (Mamo et al., 1999). Some natural organic fertilizers contain multiple N source constituents. Nitrogen availability for these fertilizers can be complex, with varying degrees of composition associated with their respective N sources. Both readily-available and recalcitrant forms of N can be found that affect rates of mineralization in natural organic fertilizers (Van Kessel et al., 2000). However, the greatest amounts of N are usually found in organic forms.

Nitrogen found in natural organic fertilizers is converted via biological decomposition, a function of N source composition (Van Kessel et al., 2000) and soil properties (Fisk and Schmidt, 1995). Garau et al. (1986) concluded that the mineralization process was more influenced by soil type than by rate and type of sludge applied. In their study, mineralization was increased with higher pH soils (7.8 vs. 5.5), 43% mean N release in a 16-wk laboratory incubation of sewage sludges at 30°C.

Fertilizer composition (amounts of total N and C) can affect rates of mineralization or immobilization. It is generally accepted that organic additions to the soil with a C:N ratio ≤20:1 will result in net NH_4^+ production. Studies have demonstrated that as the C:N ratio decreases, the amount of plant available N (NH_4^+ + NO_3^-) increases (Agehara and Warncke, 2005; Gale et al., 2006). In a field experiment, Gilmour and Skinner (1999) also found release of biosolids plant available N (PAN) to be linearly related to biosolids C:N.

Soil moisture and temperature have been found to affect decomposition of organic N materials (Agehara and Warncke, 2005). Soil moisture regulates O_2 diffusion. Heterotrophic bacteria and fungal activity responsible for the mineralization of natural organic materials were observed to be greatest when soil moisture levels were around 60% water holding capacity (Linn and Doran, 1984). Agehara and Warncke (2005) reported increasing soil moisture (50, 70, and 90% water holding capacity) increased net N released from alfalfa pellets (AP) and partially composted chicken manure (CM) 10 to 13%, but did not affect urea hydrolysis. The authors also observed increasing temperatures (15/10, 20/15, and 25/20°C day/night) increased net N released from AP, CM, and blood meal (BM) by 25, 13, and 10%, respectively.

Biosolids have been a large focal point of N transformation studies. Many have reported on their mineralization often via laboratory incubation (Ryan et al., 1973; Parker and Sommers, 1983; Barbarick et al., 1996; Adegbidi and Briggs, 2003; Wang et al., 2003). Mineralization of organic products can be influenced by the composition and formulation of raw material. Parker and Sommers (1983) observed amounts of mineralizable N from primary, waste activated, aerobically digested, and composted biosolids to be 25, 40, 15, and 8%, respectfully. Also during this study, the authors noted a rapid, initial release of inorganic N followed by a relatively constant rate of mineralization from wk 4 to 16 during incubation of primary, waste activated, and aerobically digested sludges. A similar effect was observed by Agehara and Warncke (2005) in a laboratory study where net N released for urea was 91 to 96%, 56 to 61% for BM, 41 to 52% for AP, and 37 to 45% CM during incubation for 12 wk. When anaerobically digested sludge was incubated for 16 wk at 23±3°C, 4 to 48% was found to mineralize (Ryan et al., 1973).

Many past studies have focused on the relationship between natural organic N compounds and N availability, chemical composition, soil moisture, and temperature. Often compounds in these studies contain a single N source. Natural organic N fertilizers used in turfgrass management can contain multiple N source constituents. More research is needed on N release of these products to alleviate some of the ambiguity associated with their use on turf.

MATERIALS AND METHODS

An incubation study was carried out beginning July 2007 at the Washington State University Puyallup Research and Extension Center at Puyallup, WA to evaluate inorganic N release among 9 natural organic, and three synthetic fertilizers, and an unfertilized control. Each N fertilizer contained various N source constituents. The objective of this study was to compare fertilizers based on N sources by observing differences in their associated inorganic N release ($NH_4^+ + NO_3^-$).

Nitrogen products used in this study were commercially available fertilizers. Each product contained various N source materials (Table 2.1) used in turfgrass fertilization. This study included a single treatment N fertilizer. The N fertilizer treatment consisted of 13 levels corresponding to N sources: Milorganite, Nature's Intent, Richlawn, Ringer, Whitney Farms, Soundgro, Nutri-Rich 4, Dr. Earth, Nutri-Rich 8, PCSCU, AmS13 (13% N), AmS21 (21% N), and an unfertilized control. Two of the natural organic N fertilizers (Milorganite and Soundgro) were anaerobically digested, heat-dried biosolids.

Laboratory incubations

Fertilizer inorganic N release was estimated via incubation with soil in a temperature and moisture controlled chamber. Inorganic N accumulation was measured with incubation intervals of 0, 1, 2, 4, 8, 10, 12, and 16 wk. Soil for incubation was collected in July 2007 and stored at field moisture at 4°C. Approximately 625 g (wet weight basis) of Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic, Vitrandic Haploxerolls) soil (22.9% moisture) was placed in 3.8-L poly plastic, ziptop-type bags. One of each N fertilizer was added to a corresponding bag, shaken for five minutes to mix, and a ventilation tube inserted to allow for gas exchange during incubation, reducing the potential for denitrification. Treatments were replicated four times. Nitrogen fertilizer weights were determined based on a 400 mg N kg^{-1} soil application rate. Samples were placed in an incubation chamber at 22°C. Temperature and moisture contents were ideal for mineralization. Temperatures were monitored using a HOBO external data logger (Onset Computer Corporation, Bourne, MA). Bags were removed at 1, 2, 4, 8, 10, 12, and 16 wk after treatment (WAT) and two 10±0.5 g subsamples were collected. The first set was placed into pre-tared soil moisture tins and weighed. Samples were dried in a laboratory oven

(Isotemp oven, Fisher Scientific, Pittsburgh, PA) at 65°C for 24 hr. Mass was recorded before and after drying and percentage moisture calculated as (wet wt – dry wt) ÷ (dry wt) to maintain soil moisture. The other subsample set was weighed into Erlenmeyer flasks. Soil samples were extracted with 2N KCl solution and analyzed for NH_4 and NO_3 colorimetrically. Samples were gravity filtered through Whatman #5 filter paper and stored in poly scintillation vials at -12°C until analyzed. Automated colorimetric analysis employed the salicylate method for NH_4-N and Cd reduction for NO_3-N (Mulvaney, 1996). Soil nutrient extracts were analyzed using a Lachat QuickChem® 8000 series flow injection analysis (FIA) autoanalyzer (Hach Company; Loveland, CO).

Data for all four replications was averaged for NH_4-N and NO_3-N at each observation date and presented as μg NH_4-N g $soil^{-1}$ and μg NO_3-N g $soil^{-1}$. Total N extracted was measured as the sum of soil NH_4^+ + NO_3^- and statistically analyzed. These values were then adjusted for the unfertilized control, and expressed as a percentage of N applied. This was calculated as [mean total N (μg N g $soil^{-1}$) for four replications ÷ 400 mg N kg $soil^{-1}$]*100. This data was presented graphically over the 16 wk incubation period. Sets of three N sources were selected for their corresponding figures based on amounts of total N extracted expressed as percentage of N applied.

The soil samples used in the experiment were relatively homogenous experimental units. A completely randomized design with a one-way treatment structure was used to avoid any subjective assignment of N fertilizers to the soil. Random errors associated with response of N fertilizer to soil were assumed to be independent, normally distributed with mean zero, and contain homogeneity among variances. The 13 N fertilizer treatments were replicated four times resulting in 52 experimental units.

Data were averaged for all four replicates N fertilizer treatments. All data were subject to analysis of variance using the General Linear Models procedure of SAS v9.1.2 (SAS Institute, 2004) to analyze significance ($P \leq 0.05$) of N fertilizer affect at each time of observation. When the affect of N fertilizer was significant (significant F-statistic), further analysis was conducted using Fisher's Protected LSD to compare treatment means. Correlation coefficients were generated between fertilizer C:N ratios and their respective total N extracted after one wk of incubation using SAS proc corr.

RESULTS AND DISCUSSION

The Puyallup fine sandy loam used as the incubation medium was analyzed for pH, total bases, and select nutrient contents (HL study; Appendix Table III). Laboratory soil testing indicated soil OM, measured by loss on ignition (LOI) at 400°C for 16 h was 7%. Incubation chambers were not representative of field conditions. Environmental variables such as fluxes in moisture and temperature were controlled with chamber use. Soil conditions were conducive for microbial activity, theoretically inducing maximum mineralization.

The sources and selected general characteristics of each N fertilizer used in this study are given in Table 2.1. Many of the natural organic products contain multiple N sources, mostly products of the animal and feed industry. Biosolid N sources, as products of sewage sludge activation, contained relatively similar amounts of total C and N, and therefore, similar C:N ratios. Milorganite and Soundgro are both products of anaerobically digested sewage sludge and have been subjected to similar treatment processes.

Analysis of variance (*P*<0.0001) indicated a significant N fertilizer effect at 1, 2, 4, 8, 10, 12, and 16 wk after treatment (Table 2.2). The total N extracted during the 16 wk incubation period is summarized in Table 2.3 for each time of observation. These values were adjusted by subtracting out external N from the unfertilized control, and expressed as a percentage of N applied (Fig. 2.2 to 2.5). Temperatures were relatively constant with the exception of an increase between wk 4 and 8 (Fig. 2.1). Most of the biosolid N mineralization occurred soon after application from 0 WAT to 1 WAT, which agrees with Muchovej and Rechcigl (1998) (Table 2.3). Inorganic N release was highest during the first week of incubation as indicated by a rapid increase in total N extracted for all N fertilizer treatments (Table 2.3; Fig. 2.2 to 2.5). There were significantly higher amounts of total N extracted from N fertilizer treated soils than from the unfertilized control beginning 1 WAT (Table 2.3). With the exception of Nature's Intent, all amendments contained a portion of water-soluble N (Table 2.1). This fraction would have quickly dissolved in the soil solution. These results are substantiated by other research. In a study conducted by Gale et al. (2006), rapid decomposition of fresh and composted soil amendments was noted within the first 7 to 30 days of incubation in soil at 22°C. Wang et al. (2003) observed similar results in a biosolid incubation study. A rapid increase in the NO_3^- proportion of mineralized N (total of soil $NH_4^+ + NO_3^- + NO_2$) was found after one wk of incubation at 20°C. N sources consisted of anaerobically and aerobically digested municipal biosolids, and two pulp and paper industrial biosolids from two aerated wastewater stabilization lagoons applied at 400 mg N kg^{-1} soil. In another study, Parker and Sommers (1983) observed greatest N mineralization rates with anaerobically digested sewage sludge from 0 to 2 wk after initial incubation at 23°C.

After the first week of incubation, N fertilizer treatments appeared to exhibit a relatively stable amount of total N extracted through 16 wk. The initial rapid release of N followed by a slow phase indicates the organic N fraction of the natural organic materials may contain unstable forms that are mineralized quickly and stable forms more resistant to mineralization. Gilmour et al. (2003) observed two phases of decomposition based on CO_2 evolution in a laboratory study. In that study, municipal biosolids with mean C:N of 7.5 were incubated in or on soil at 25°C of optimum moisture. A mean rapid and slow fraction rate of decomposition with constants 0.021 and 0.0015 d^{-1} was noted. The AmS13 and AmS21, not containing organic N, were significantly higher in total N than all other treatments at 1 WAT (Table 2.3). The PCSCU, Ringer, Richlawn, and Dr. Earth treatments were not significantly different and exhibited less extractable soil N than AmS13 and AmS21. This was pattern of N release was followed by Whitney Farms and Nutri-Rich 8. Amounts of total N extracted were significantly lower for Soundgro, Nature's Intent, and Nutri-Rich 4 vs. other N fertilizers.

Differences in N release patterns from these and other N fertilizers could have been a result of their chemical compositions. Gale et al. (2006) observed amendment C:N to be an approximate indicator of mineralization potential in a laboratory study. As the C:N ratio decreased, the amount of plant available N ($NH_4^+ + NO_3^-$) increased (Agehara and Warncke, 2005; Gale et al., 2006). With the exception of Richlawn, all N fertilizers used in this study exhibited this relationship. Correlation coefficients between total N extracted at 1 WAT and C:N ratios confirmed this observation (R^2=0.74; P=0.0002). Total N extracted from Richlawn treated soils was not significantly different from Ringer 1 WAT had a higher C:N ratio (5.9). Its higher C:N was probably a result of its constituents, with dried poultry manure containing feces, urine, and uncomposted bedding. Manures containing materials with cellulosic wastes (high C bedding materials) are likely to have an immobilizing effect (Van Kessel et al., 2000). A similar inconsistency with rates of mineralization based on C:N ratio of incubated soils was found by Bengtsson et al. (2003). The authors concluded that differences in gross N mineralization and immobilization were more related to soil respiration rate and ATP content, a reflectance of soil biomass and microbial metabolism. These were not measured in the current study.

The total N extracted and C:N ratio relationship was also apparent between the Whitney Farms, Ringer, Nutri-Rich 4, and Soundgro treatments. Total N extracted was significantly higher for the Whitney Farms and Ringer treatments at 1, 2, 4, 8, 10, and 16 WAT vs. Nutri-Rich 4 and Soundgro. Ringer had a relatively low C:N ratio (3.2) while the C:N ratio for Whitney Farms was 4.3. Nutri-Rich 4 contained the highest C:N ratio (8.7) followed by Soundgro (6.1). Total N extracted from soils treated with these higher C:N materials was significantly lower.

In terms of natural organic N fertilizers, there was generally significantly lower total N extracted in soils containing biosolid N sources and Nutri-Rich 4 vs. Nature’s Intent, Nutri-Rich 8, Ringer, Richlawn, and Whitney Farms (Table 2.3). Significant differences between N sources were most apparent at 2 and 4 WAT. Nitrogen fertilizers could be grouped into four brackets in terms of decreasing amounts of total N extracted: 1) AmS13, AmS21, and PCSCU; 2) Ringer, Richlawn, and Dr. Earth; 3) Whitney Farms, Nature’s Intent, and Nurti-Rich 8; and 4) Milorganite, Soundgro, and Nurti-Rich 4. Total N extracted was usually not significantly different for N sources within each group, but was significantly different for each N fertilizer outside of its respective group. Among the three N fertilizers in Group 2 there were no common constituents, while N fertilizers in Group 3 all contained feather meal. However, Ringer and Dr. Earth of Group 2 also contained feather meal and, thus, rates of inorganic N release could not be characterized based on this constituent. Nitrogen fertilizers in Group 4 included biosolids and dried poultry waste, which were not found in any other groups. These seemed to behave similarly, mineralizing more slowly than other N source constituents. After 16 wk of incubation, total N extracted from AmS13, AmS21, and PCSCU treated soils was significantly higher than other N fertilizer treated soils.

Amounts of total N extracted expressed as percentage of N applied was observed highest at one of two observation dates for N fertilizers (Fig. 2.2 to 2.5). There appeared to be two distinct inorganic N release plateaus that occurred: 2 WAT for the AmS13, Soundgro, Ringer, Richlawn, Nutri-Rich 4, Nutri-Rich 8, and Dr. Earth and 10 WAT for AmS21, PCSCU, Milorganite, Whitney Farms, and Nature's Intent. Two distinct phases of N release were found by Agehara and Warncke (2005) during an incubation study of AP, BM, and CM at 10 to 25°C. A rapid phase was observed in the first 2 wk of incubation where a mineralization plateau was reached with AP and BM. Afterwards, these sources showed a steady N release until the end of the 12 wk incubation while chicken manure wasn't observed to reach plateau mineralization until wk 8 to 12. This was not the case in the current study. Richlawn composed of dried poultry manure appeared to reach an inorganic N release plateau at 2 wk, unlike the 8 to 12 wk observed by Agehara and Warncke (2005). This plateau did not appear to correspond to respective N fertilizer C:N ratios, as discussed above where N sources with higher C:N ratios would be expected to mineralize more slowly than N sources with lower C:N ratios, or to amounts of WSN (Table 2.1). These plateaus may be used to describe general behavior of each individual N source, corresponding to periods of peak inorganic N release.

Approximately 31 to 43% of applied N was released from Soundgro, Milorganite, and Nutri-Rich 4 treated soils during the study (Fig. 2.5). Values observed for other natural organic N sources ranged from 34 to 68% (Fig. 2.3 and 2.4), while the AmS and PCSCU standards were 73 to 87% (Fig. 2.2). Studies have indicated only partial biosolid decomposition of 4 to 48% of the organic N in sewage sludges within 16 wk of incubation (Ryan and et al., 1973; Parker and Sommers, 1983; Garau et al., 1986) probably due to complex forms of recalcitrant N. Cogger et al. (2004) estimated plant available N to be 37±5% within the first yr for nonlagoon treated biosolids. In a 67 d laboratory incubation, Douglas and Magdoff (1991) observed mineralization of these sludges to be 23 to 41%. Garau et al. (1986) reported 16 to 41% after incubation for 16 wk at 30°C while Ryan et al. (1973) found 4 to 48% of organic N in sewage sludge was mineralized to (NO_3+NO_2)-N in 16 wk at 23±3°C.

Reports by Ryan et al. (1973) also indicate that rates of sewage sludge addition may have an impact on the amount of N recovered. Recovery of added inorganic N was found to decrease with increased sewage sludge additions (>235 mg N kg^{-1} soil), possibly due to denitrification. They observed a decrease in (NO_3+NO_2)-N coupled with decreased NH_4^+ between the 12th and 16th wk of incubation associated with denitrification due to anaerobic conditions. Even though microbial denitrification is an anaerobic process, anaerobic soil microsites can exist in apparently well drained soils causing denitrification (Parkin, 1987).

In the current study, total N extracted when expressed as a percentage of N applied was found to decrease for all N source treated soils during incubation at 10 to 12 WAT (Fig. 2.2 to 2.5). The majority of this loss occurred as NO_3-N (data not shown). However, during this time inorganic N release appeared to increase for the unfertilized soil, indicating an effect due to N treatment. It is unlikely that anaerobic conditions existed. Soil moisture content, associated with anaerobic conditions, never exceeded 25% w/w. This soil moisture content was used in a similar incubation study by Gale et al. (2006), also with a Puyallup fine sandy loam soil. Biological denitrification may be of little importance where aerobic conditions exist, such as surface applications, but could have an effect where subsurface banded applications are used.

Nitrogen immobilization can affect NO_3^- availability, a likely avenue of N loss observed in the current study during incubation from 10 to 12 WAT. Organic substrate C availability has been found to influence N cycling. Nitrogen immobilization can be increased with increasing soil OM content (Barrett and Burke, 2000). In their study, increased rates of N immobilization were found in soils containing active microbial populations. Increased C mineralization was found on plant covered vs. non-covered soil and accompanied by N immobilization due to the presence of organic C substrate. Epstein et al. (1978) found that raw sludge high in available C and significant quantities of NO_3-N can be lost by denitrification and immobilization soon after application. It cannot be concluded in the current study whether denitrification or immobilization was responsible for the decline in total N observed during incubation from 10 to 12 WAT.

CONCLUSIONS

The results of this study showed that after 16 wk of incubation, total N extracted (NO_3^- and NH_4^+) varied across a range of N fertilizers. Similarities were observed between fertilizers based on N sources. Greatest amounts of total N extracted were observed for the AmS13, AmS21, and PCSCU fertilizers, which contained synthetic N sources. Less inorganic N was released from Nutri-Rich 4, Milorganite, and Soundgro in comparison to other fertilizers. Similar amounts of total N extracted between these products indicate that dried poultry waste alone may behave similarly to anaerobically digested biosolids. No differences between Nature's Intent, Richlawn, Ringer, Whitney Farms, Nutri-Rich 4, Nutri-Rich 8, and Dr. Earth fertilizers could be concluded based on their respective N sources. There was little consistency characterizing N fertilizers based on their N sources and inorganic N release. Inorganic N release between each product may be better estimated in relative comparison to their C:N ratios as compared to source materials.

In this laboratory study, a large fraction of fertilizer N was collected after the first wk of incubation. Due to variability of temperature and moisture, amounts of inorganic N released may differ when applied in a field setting. Product composition appeared to have an effect on inorganic N release upon application. As N solubility increased, total N extracted increased. Once presumed unstable N fractions were released, amounts of total N extracted were relatively constant through 16 wk. The observed N decrease from 10 to 12 WAT may have been due to denitrification or immobilization. Applicators should be cautious of methods used to apply these products, whether surface applied or banded as environmental conditions could play a role in their behavior and subsequent N fate.

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Table 2.1. Selected properties of N sources.

Product name and manufacturer	% WSN* % WIN**	Total C (%)	Total N (%)	C/N ratio	Nutrients derived from
Milorganite 6-2-0 Milwaukee Sewerage Commission Milwaukee, WI	0.5% WSN 5.5% WIN	35.2	6.3	5.6	Biosolids
Nature's Intent 9-3-4 Pacific Calcium Tonasket, WA	9% WIN	39.5	8.9	4.4	Feather meal, steamed bone meal, potassium sulfate, gypsum
Richlawn 5-3-2 Richlawn Turf Good Inc. Platteville, CO	1.2% WSN 3.7% WIN	34.6	5.9	5.9	Dried poultry manure
Ringer Lawn Restore 10-2-6 Woodstream Lititz, PA	2.4% WSN 7.6% WIN	33.4	10.3	3.2	Hydrolyzed poultry feather meal, nitrate of soda, potassium sulfate, bone meal, soybean meal
Whitney Farms 8-2-4 Rod McLellan Company Independence, OR	2% WSN 6% WIN	36.1	8.3	4.3	Blood meal, dried poultry waste, feather meal, bone meal, sulfate of potash magnesia
SoundGro 5-4-0 Pierce County, WA Public Works and Utilities University Place, WA	0.7% WSN 5.2% WIN	35.1	5.7	6.1	Biosolids
Nutri-Rich 4-3-3 D. Stutzman Farms Canby, OR	1.2% WSN 2.7% WIN	24.2	2.7	8.7	Dried poultry waste
Dr. Earth 9-3-5 Dr. Earth Company Los Angeles, CA	2.5% WSN 6.5% WIN	25.1	7.6	3.3	Fish meal, bone meal, feather meal, potassium sulfate, alfalfa meal, calcium sulfate, seaweed extract
Nutri-Rich 8-2-4 D. Stutzman Farms Canby, OR	1.5% WSN 6.5% WIN	37.6	8.6	4.4	Dried poultry waste, blood meal, feather meal, sulfate of potash
Short-Kut 16 with Trikote 16-2-16 J.R. Simplot Company Lathrop, CA	7% quickly available N 9% slowly available N	5.5	12.1	0.5	polymer coated sulfur coated urea, ammonium phosphate sulfate, potassium sulfate, and ferrous oxides

Table 2.1 continued.

Ammonium sulfate 13-2-13 The Anderson's Lawn Fertilizer Division Maumee, OH	13% quickly available N	4.4	13.0	0.3	Ammonium phosphate, ammonium sulfate, potassium sulfate, ferric oxide, ferrous sulfate, cupric oxide, cupric sulfate, manganous oxide, managnese sulfate, zinc oxide, and zinc sulfate
Ammonium sulfate 21-0-0 Waupaca Northwoods LLC Waupaca, WI	21% quickly available N	3.6	21.0	0.2	ammonium sulfate
Unfertilized control Native soil	N/A	3.3	0.2	15.1	N/A

*Water soluble N (percentage by weight).
**Water insoluble N (percentage by weight).

Table 2.2. Analysis of variance of total N (NH_4^+ + NO_3^-) mineralized in response to N fertilizer treatments.

		Weeks after treatment							
Source	DF	0	1	2	4	8	10	12	16
N source	12	ns†	**	**	**	**	**	*	**
Error	39								
Corrected Total	51								

*, ** Significantly different at *P*=0.05, 0.01, respectively.
†ns=not significant.

Table 2.3. Analysis of variance of total N mineralized (µg N g^{-1}soil) as affected by N fertilizer at 22°C for 12 N fertilizer treatments and an unfertilized control in a Puyallup fine sandy loam soil.

	Weeks after treatment							
Fertilizer	0	1	2	4	8	10	12	16
Unfertilized	46	48	52	65	102	80	138	88
AmS13	43	372	387	395	428	398	369	387
AmS21	43	353	367	362	430	415	386	382
PCSCU	44	298	344	396	411	428	327	396
Milorganite	45	203	214	216	262	252	268	257
SoundGro	46	174	187	190	232	212	226	209
Whitney Farms	42	223	274	267	310	316	327	298
Ringer	44	259	326	310	356	346	304	330
Nature's Intent	42	149	244	256	305	292	285	273
Richlawn	45	292	310	317	310	320	297	296
Nutri-Rich 4	45	201	217	203	236	239	267	235
Nutri-Rich 8	45	239	263	260	301	279	314	301
Dr. Earth	43	306	319	317	313	317	317	304
lsd‡	ns†	44	19	19	25	38	101	33

†ns=not significant.
‡Fisher’s protected Least Significant Difference (*P*=0.05).

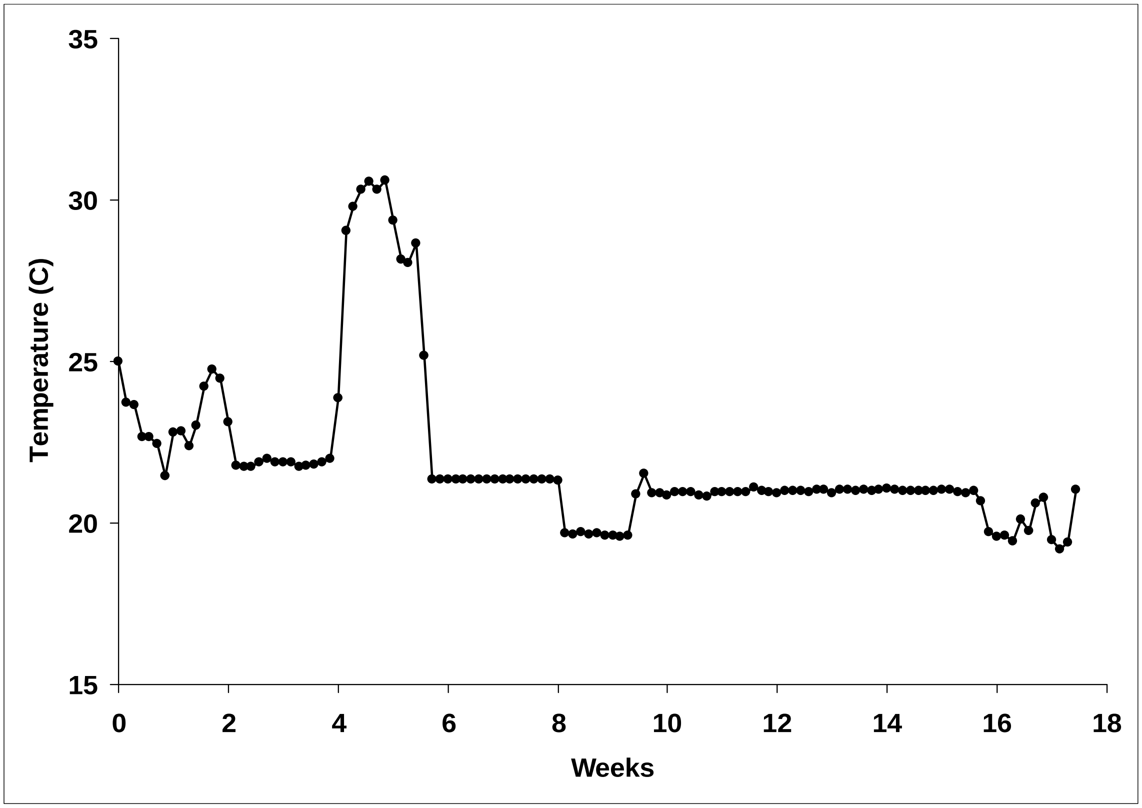

Fig. 2.1. Mean daily temperatures of the mineralization / incubation chamber.

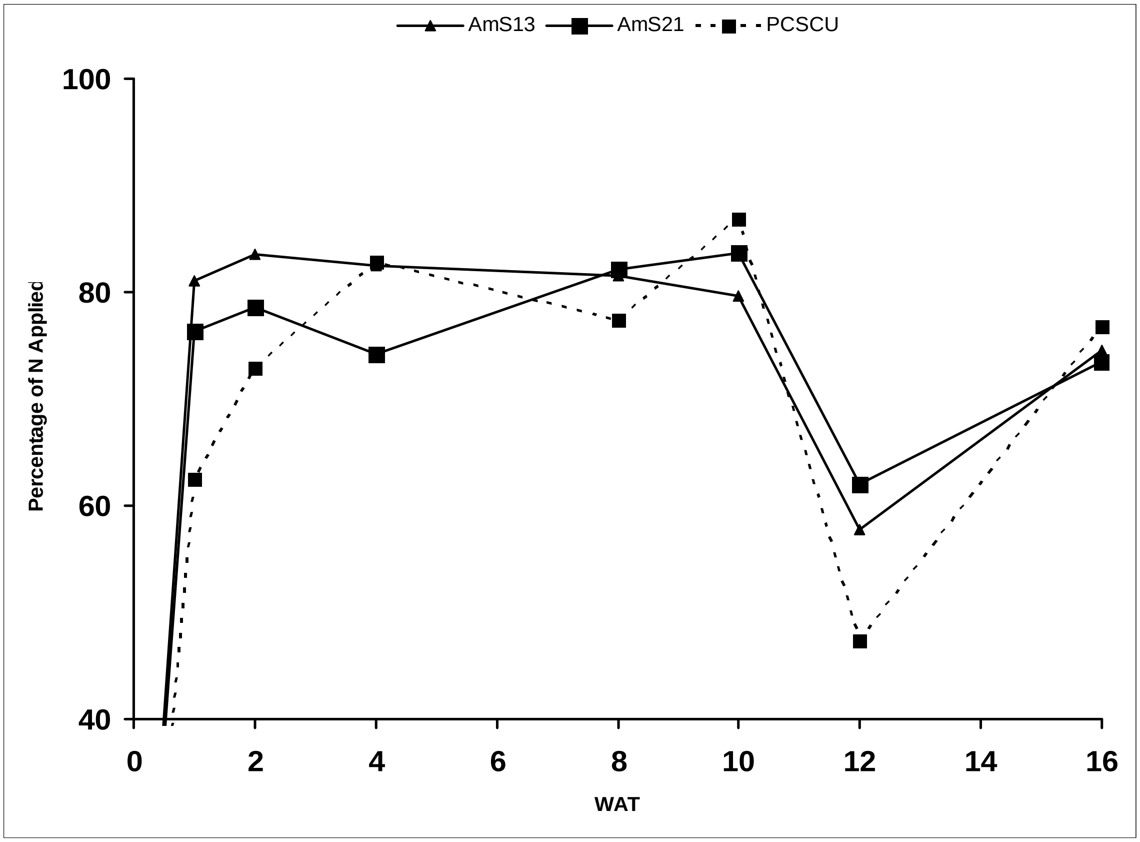

Fig. 2.2. Total soil extractable N ($NH_4^+ + NO_3^-$) expressed as percentage of N applied as affected by AmS13, AmS21, and PCSCU N sources incubated for 16 wk after treatment (WAT) at 22°C in a Puyallup fine sandy loam soil adjusted for unfertilized control.

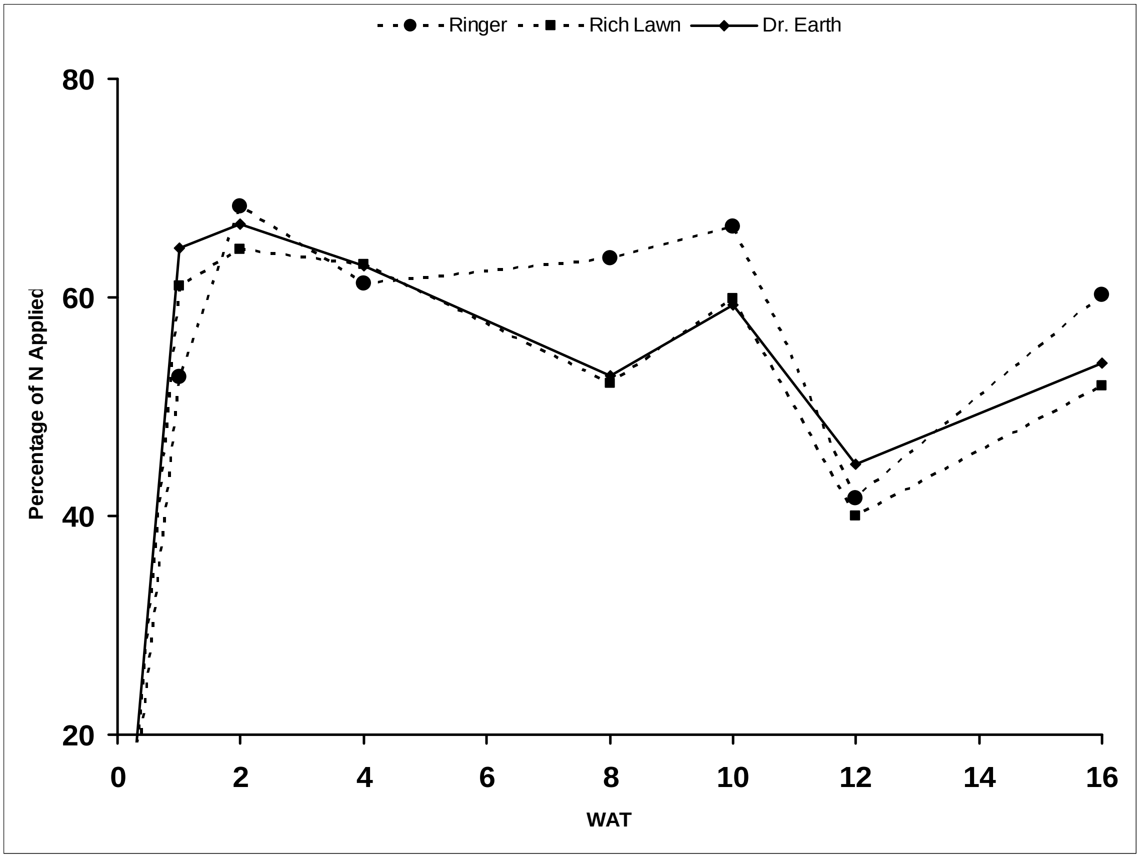

Fig. 2.3. Total soil extractable N (NH_4^+ + NO_3^-) expressed as percentage of N applied as affected by Ringer, Richlawn, and Dr. Earth N sources incubated for 16 wk after treatment (WAT) at 22°C in a Puyallup fine sandy loam soil adjusted for unfertilized control.

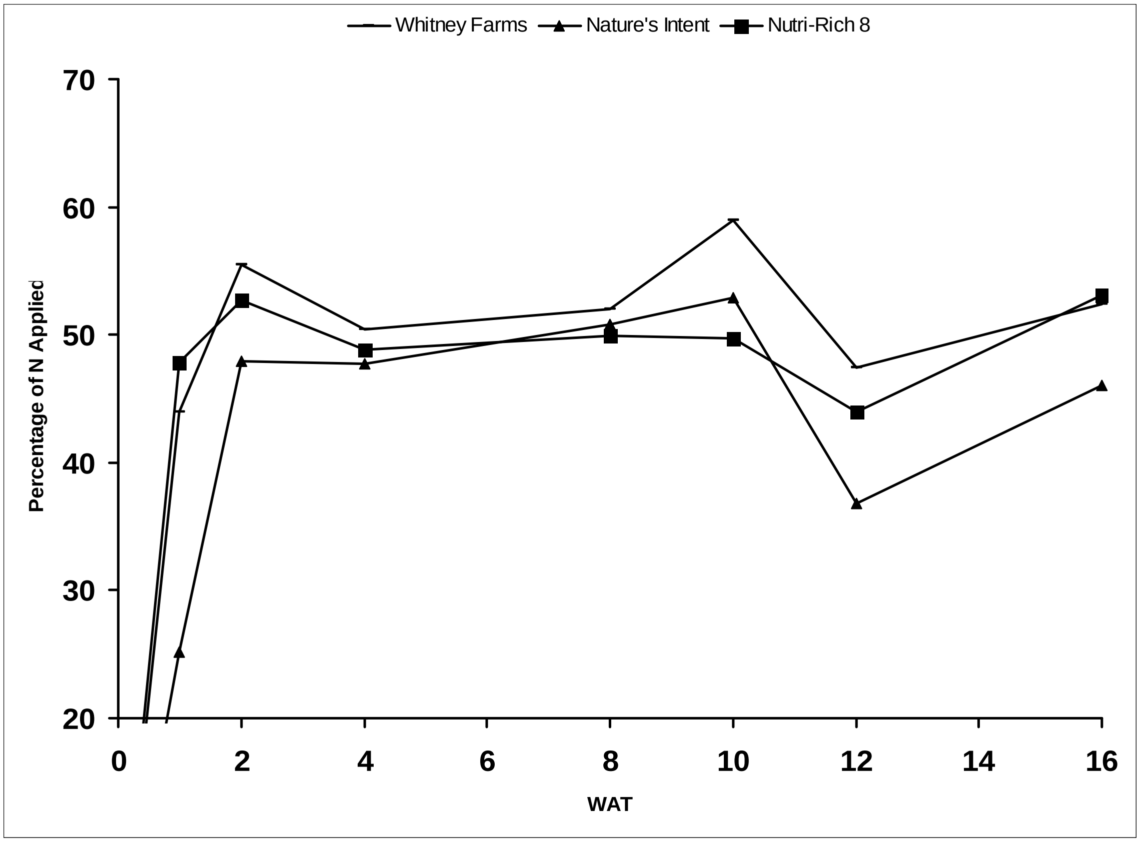

Fig. 2.4. Total soil extractable N ($NH_4^+ + NO_3^-$) expressed as percentage of N applied as affected by Whitney Farms, Nature's Intent, and Nutri-Rich 8 N sources incubated for 16 wk after treatment (WAT) at 22°C in a Puyallup fine sandy loam soil adjusted for unfertilized control.

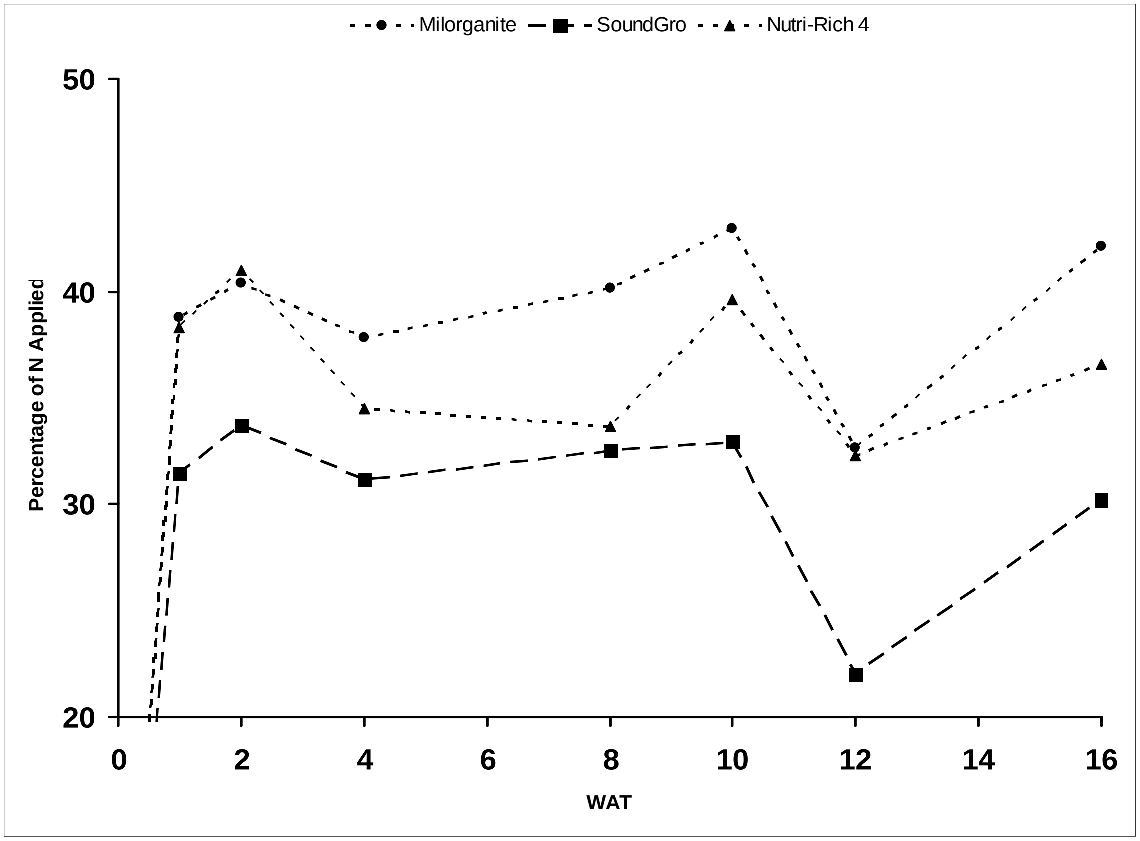

Fig. 2.5. Total soil extractable N ($NH_4^+ + NO_3^-$) expressed as percentage of N applied as affected by Milorganite, Soundgro, and Nutri-Rich 4 N sources incubated for 16 wk after treatment (WAT) at 22°C in a Puyallup fine sandy loam soil adjusted for unfertilized control.

Appendix Tables

Appendix Table I. Pollutant concentration limits for class “A” biosolids.

Trace element	Max concentration limits for all land applications (mg per kg)[a]	Pollutant concentration limits for exceptional quality biosolids (mg per kg)[a]
Arsenic	75	41
Cadmium	85	39
Chromium	3000	1200
Copper	4300	1500
Lead	840	300
Mercury	57	17
Molybdenum[b]	75	18
Nickel	420	420
Selenium	100	36
Zinc	7500	2800
Applies to:	All land applied biosolids	Bulk biosolids and bagged biosolids[c]

[a] Dry weight basis
[b] Molybdenum limits deleted from the Part 503 rule pending EPA reconsideration
[c] Bagged biosolids include those given away in bags or other containers

Adapted from US Environmental Protection Agency, 1995.

Appendix Table II. Essential turfgrass nutrients.

Element	Symbol	Dry Weight (%)	Primary Forms Used
NON-MINERAL ELEMENTS			
Hydrogen	H		H_2O (l), H^+
Oxygen	O		H_2O (l), O_2 (g)
Carbon	C		CO_2 (g)
MINERAL ELEMENTS			
Major Nutrients (%)			
Nitrogen	N	3.0 to 4.8	NH_4^+, NO_3^-
Phosphorus	P	0.4 to 0.6	HPO_4^{2-}, $H_2PO_4^-$
Potassium	K	1.5 to 2.5	K^+
Secondary Nutrients (%)			
Calcium	Ca	0.45 to 1.0	Ca^{2+}
Magnesium	Mg	0.25 to 0.5	Mg^{2+}
Sulfur	S	0.25 to 0.4	SO_4^{2-}
Micronutrients (ppm)			
Iron	Fe	40 to 100	Fe^{3+}, Fe^{2+}
Manganese	Mn	50 to 150	Mn^{2+}
Zinc	Zn	30 to 65	Zn^{2+}
Copper	Cu	5 to 15	Cu^{2+}
Boron	B	10 to 40	H_3BO_3 (Boric Acid)
Molybdenum	Mo	Trace	MoO_4^{2-}
Chlorine	Cl	Trace	Cl^-

Modified from Emmons, 2000.

Appendix Table III. Site soil analyses.

	pH	P ppm	K ppm	Ca meq/100g	Mg meq/100g	Total Bases	Organic Matter (%)†	SMP Buf. pH
HL[‡]	4.8	26	220	10.9	1.6	13.1	7.4	6.2
FW[¶]	6	25	93	3.6	0.3	4.1	1.1	7.7

[†] Percentage OM content calculated via mass loss on ignition (LOI).

[‡] Perennial Ryegrass plot area maintained at home lawn conditions.

[¶] Colonial Bentgrass and Fine Fescue mix plot area maintained at golf course fairway conditions.

Appendix Table IV. Metal content of utilized biosolid fertilizers.

	Milorganite®	SoundGRO™
	ppm	ppm
Arsenic	8.0	3.5
Cadmium	3.0	1.6
Cobalt	5.4	220
Mercury	0.45	0.7
Molybdenum	10	14.2
Nickel	30	9.4
Lead	71	18.0
Selenium	3.0	8.4
Zinc	510	799.3
Chromium	270	11.4
Copper	250	516.6

Appendix Table V. Soil particle size analysis of FW study including United States Golf Association specifications.

Particle Size (mm)	3.4	2.0	1.0	0.5	0.25	0.15	0.05	<0.05
Fraction (%)	1.1	1.2	7.3	26.2	49.6	10.8	2.5	1.1
USGA Specifications	3% max 2 - 3.4			60% min 0.25 - 1		20% max	5% max	8% max
		10% max 1 - 3.4					10% max < 0.15	