Effect of Real and Simulated Traffic on Coated Fertilizer Prill Integrity and Nitrogen Release

by

Cheng Qian

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 08, 2017

Keywords: polymer-coated fertilizers, turfgrass, damage,
athletic traffic, traffic simulator, nitrogen release

Approved by

Elizabeth Guertal, Chair, Professor of Crop, Soil and Environmental Sciences
David Y. Han, Associate Professor of Crop, Soil and Environmental Sciences
Steve Li, Assistant Professor of Crop, Soil and Environmental Sciences
Xiaoyu Li, Assistant Professor of Mathematics and Statistics

Abstract

The amount of nitrogen (N) from air and soil is not sufficient to produce high quality turfgrass, and thus N fertilizers are often applied. Urea is the most widely-produced and commonly-traded N fertilizer, containing 46% nitrogen by weight. However, it can lead to environmental issues due to its water solubility. One solution is to use slow-release fertilizers, of which polymer-coated urea (PCU) is an example. A slow-release fertilizer such as PCU meters N out over a long period, with N release rates that may vary from 10 to 30 weeks. In high-traffic areas such as football fields or lacrosse fields, one question is the impact that human traffic may have on the integrity of PCU prills. The objective of this project was to 1) examine N release from coated N fertilizer sources as affected by traffic; and 2) examine N release from fertilizer sources as affected by artificial or real foot traffic. Four studies were included, with two short term experiments (1 week) and two long term experiments (9 weeks), using 6 different types of fertilizers. Traffic included natural and artificial foot traffic, with N release determined. Data showed the use of artificial traffic affected and damaged prill coatings, while damage was not significant with natural foot traffic. N sources with a thicker coating tended to be less affected by traffic.

Acknowledgments

I would like to thank my major professor Dr. Elizabeth A. Guertal for her help on guiding and supporting me during my graduate program at Auburn University. Without her help, I could not start my exciting research or finish the thesis. I also want to extend my thanks to the other committee members Dr. David Y. Han, Dr. Steve Li and Dr. Xiaoyu Li.

I also want to thank our lab technician Mr. Bill Bryce and all student workers in the turfgrass lab for helping me set up and pick up research samples. I want to convey my appreciation to Dr. Charles Z. Ogles, who helped with my research problems, and Miss. Pan Wang for assisting me taking samples and practicing my presentation.

Last but not least, I would like to thank my lovely boyfriend Jeff Savonen for always understanding and being there for me. I am especially grateful to my father Jianwei Qian and my mother Xuemei Dai for their support and giving me the opportunity to study aboard and see the world.

Table of Contents

Abstract ii

Acknowledgments iii

List of Tables v

List of Figures vi

List of Abbreviations viii

Chapter 1 Literature Review 1

- Nitrogen 1
- Nitrogen cycle 1
- Nitrogen fertilizers 7
- Methods to determine N release from coated N sources 14
- Traffic simulators 17
- Measuring the extent of damage to PCU coatings by traffic or handing 19
- Objective 21

Chapter 2 Materials and Methods 22

Chapter 3 Results and Discussion 27

Chapter 4 Conclusions 31

References 32

Appendix 1 45

Appendix 2 54

List of Tables

Table 1 Fertilizers and treatment dates of experiments 45

Table 2 Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 1 46

Table 3. Percent N release as affected by traffic and N source, artificial traffic applied, Experiment 1 47

Table 4. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 2 48

Table 5. Percent N release as affected by traffic and N source, real human traffic applied, Experiment 2 49

Table 6. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 3. 50

Table 7. Comparison of nitrogen release percentage between different sampling dates by Cady traffic simulator. Experiment 3. 51

Table 8. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 4 52

Table 9. Comparison of nitrogen release percentage between different sampling dates by Cady traffic simulator. Experiment 4 53

List of Figures

Figure 1. The Cady traffic simulator unit, used to apply artificial traffic in Experiments 1 and 3 54

Figure 2. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 1, Experiment 1 55

Figure 3. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 3, Experiment 1 56

Figure 4. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 7, Experiment 1, ... 57

Figure 5. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 7, Experiment 2 58

Figure 6. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 1, Experiment 3, ... 59

Figure 7. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 3, Experiment 3 60

Figure 8. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 5, Experiment 3, Auburn, AL 61

Figure 9. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 7, Experiment 3 62

Figure 10. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 9, Experiment 3 63

Figure 11. N release by sampling date as affected by coating thickness, trafficked (artificial) plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 3. 64

Figure 12. N release by sampling dates as affected by coating thickness, non-trafficked plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 3. 65

Figure 13. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 1, Experiment 4 66

Figure 14. N release by sampling date as affected by coating thickness, trafficked (real human) plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 4. 67

Figure 15. N release by sampling dates as affected by coating thickness, non-trafficked plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 4. 68

Figure 16. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 3, Experiment 4 69

Figure 17. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 5, Experiment 4 70

Figure 18. N release of fertilizer sources as affected by coating thickness. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 7, Experiment 4 71

List of Abbreviations

Nitrogen (N)

Carbon:Nitrogen (C:N)

Polymer-Coated Urea (PCU)

Sulfur-Coated Urea (SCU)

Methylene Urea (MU)

Ureaformaldehyde (UF)

Slow-release Fertilizer (SRF)

I. LITERATURE REVIEW

Nitrogen

Nitrogen (N) is a mineral nutrient required by plants for growth and development. In turfgass, nitrogen promotes vigor, visual quality, recovery from damage, and overall health (Bowman et al., 2002). Most N in the soil is in the organic form, which is not directly available for plant uptake. For turfgrass, additional N fertilizer is needed to produce high quality turf. Nitrate (NO_3) and ammonium (NH_4) are the two forms that can be assimilated and used by turfgrass. Almost always applied in the greatest amount as compared to other fertilizer nutrients, N is linked to plant vegetative growth, flowering, leaf quality, chlorophyII content, and protein in grain (Bi et al., 2008). Although its application provides profound agronomic benefits, over-application can also produce negative agronomic effects, including lodging (Basak et al., 1962), disease (Huber and Watson 1974; Golembiewski and Danneberger, 1998), insects (Daane et al., 1995), and poor fiber quality (Madani and Oveysi, 2015). Over-application of N can also lead to environmental consequences, including nitrate leaching (Snyder et al., 1984) atmospheric loss by volatilization (Torello et al., 1983) or denitrification (Horgan et al., 2002; Gross et al., 1990). The environmental impact of N on turfgrass will be discussed in greater detail later in this Introduction.

The Nitrogen Cycle

Nitrogen is found in many forms in soil. The entire system of N transformation is usually called the ‘Nitrogen Cycle’. The nitrogen cycle is a cyclic web of reactions and processes, which is affected by a wide range of factors, including soil moisture, soil temperature, soil pH, oxygen status, gases (Stevenson and Cole, 1999) and a wide range of soil physical and chemical properties (Lamb et al., 2014). Over all factors, temperature affects nitrogen transformation most, especially mineralization. Soil moisture influences the N cycle by changing microbial activity. Nitrogen and its availability for plant use are linked through the N cycle. Applied fertilizer N also becomes a part of the cycle, whenever organic or inorganic N sources are applied. Each process results in either N being made plant-available (nitrate-N and ammonium-N) (Bowman et al., 2002) or being lost from plant use (Gross et al., 1990). Soil microorganisms play an important role in the N cycle (Li et al., 2016). They serve as an agent of N transformation (Fierer et al., 2012) by making N plant-available from decayed plant residues in soil (Stevenson and Cole, 1999). Microbial activity also leads to N losses through denitrification, volatilization and immobilization.

a. Nitrogen Additions

Nitrogen can be made plant-available through mineralization, nitrification, ammonization, and microbial symbiosis (Mylona et al., 1995), and via rainfall.

Nitrogen mineralization happens near the soil surface of agroecosystems (Muruganandam et al., 2009). In mineralization, bacteria, fungi and protozoa digest organic N material and release inorganic ammonium and nitrate (Clarholm et al., 1981) via enzyme activity (Sinsabaugh, 1994). Mineralization has three steps: 1) ammonization, 2) ammonification, and 3) nitrification. Ammonization first produces amines and amino acids. Then, ammonification releases ammonia

(NH_3) and ammonium (NH_4^+) from organic matter, with various heterotrophic organisms causing this conversion.

The carbon: nitrogen (C: N) ratio affects this process. When soil organic matter, with a low C: N ratio (< 20:1), such as grass clippings are added, bacteria and fungi in the soil increase their rate of N ammonification and release NH_4^+ (Ferris et al., 1998). The ammonia produced via ammonification may be lost from the soil N cycle by being taken up by plants or fixed by illitic clay or, volatilized as ammonia gas. Alternatively, it can enter the final step of mineralization, called nitrification. Maximum nitrification occurs when soil temperature is between 30-35°C (Carrow et al., 2001). There are two distinct steps in nitrification: the first is when ammonium is oxidized to nitrite by *Nitrosomonas* and *Nitrospora* bacteria, and the second is when nitrite is oxidized to nitrate by *Nitrobacter* (Bremner, 1965). Around 10 to 20% soil oxygen, by volume, is required for nitrification, since oxygen is required in both steps. Soils with high moisture or high bulk density are more likely to have lower rates of nitrification.

Another process that adds nitrogen into the N cycle is symbiotic N fixation, which involves several different groups of organisms. The first process uses leguminous plants, who get their nitrogen directly from atmospheric nitrogen via fixation of N in a symbiotic relationship with Rhizobium (Allos and Bartholomew, 1955). Over 2×10^9 kg of N is fixed annually in legume systems, with an average of 55 kg of N ha^{-1} fixed per year in the United States (Carrow et al., 2001). The exact amount does vary with soil temperature, and residual soil N. Fixation of N by legumes mainly happens when available mineral N in the soil is low, since high levels of inorganic N inhibits the process (Carrow et al., 2001).

Asymbiotic N fixation is another type of biological nitrogen fixation. These systems use various free-living organisms to fix atmospheric nitrogen. One of the first identified organisms was the anaerobic heterotroph *Clostridium pasteurianum*, a bacteria able to use molecular nitrogen during anaerobic periods, usually after raining. It is found in soil, and has a high tolerance for acidic soil. Another is the aerobic heterotroph *Azotobacter spp.*, typically found in near-neutral or slightly alkaline soils soils, discovered in 1900 by Beijerineck (Allen and Arnon, 1955). Nitrogen from asymbiotic fixation has been shown to have a positive influence on the rhizospheres of corn, oat and soybean, but have little effect on lawn grasses (Kole et al., 1988). The photosynthetic *Rhodospirillum*, which requires both light and anaerobic condition, is a free-living photosynthetic N_2-fixation bacteria. It is usually found as a layer over mud under an algae layer.

Another method of creating plant-available N is via lightning fixation. Around 5 to 8% of the total N fixation (around 11×10^{12} g per year of N_2 fixation) is created by the enormous energy of lightning. This N is produced by the reaction between atmospheric oxygen and N_2 and nitrogen oxides (NO and NO_2) are produced. These nitrogen oxides dissolve into rainfall and become a natural N fertilizer (Hill et al., 1980). The amount of plant-available N deposited annually by this process is low, not more than 10 kg ha^{-1} year (Zahran, 1999).

Since there is not enough readily plant-available nitrogen in the soil to support high quality crops or turfgrass, N fertilizers are used in these systems. Nitrogen fertilization will increase yield, organic matter digestibility, green leaf mass and metabolizable proteins (Peyraud and Astigarraga, 1998). However, long-term application of synthetic N fertilizers might lead to a decrease in soil organic matter, because they accelerate the rate of oxidation or decay of soil organic matter (Ladha et al., 2011). Fertilizers that contain ammonium or produce ammonium, also lead to an acidification and lower pH of soils (Carrow et al., 2001).

b. Nitrogen Losses

Nitrogen can be lost from the N cycle via gaseous loss, leaching (Bowman et al., 2002), denitrification, immobilization, volatilization, plant uptake and clay fixation (Petrovic, 1990).

Nitrogen leaching occurs when the nitrate anion (NO_3^-) is moved by water below the root zone. Nitrate leaching can cause human health problems and water pollution. It is most likely to occur in sandy soil (Rieke and Ellis, 1974), especially if coupled with a high N rate and excessive irrigation (Trenholm et al., 2012). Nitrate leaching can be reduced by splitting N applications, or using slow-release N sources (Rieke and Ellis, 1974). Two main activities to reduce leaching in turfgrass are: 1) keeping irrigation water from moving below the active rooting zone, and 2) keeping N fertilization rate within N requirements (Barton and Colmer, 2006). During a leaching study using gravity lysimeters, different N sources (polymer-coated urea, sulfur-coated urea and ammonium phosphate) were used. In general, nitrate-N in leachate from coated fertilizers was low, when N fertilizer was applied at either 98 or 49 kg ha^{-1} (Telenko et al., 2015). Suction cup lysimeters can also be used to measure N leaching in soils (Barton and Colmer, 2006). Unlike column studies, they do not need to have water added while sampling, because of the pressure from suction. However, samples by suction lysimeters sample all water, and not just downward gravity flow (Starr and DeRoo, 1981). Thus, water samples of leachate collected via gravity lysimeters are considered more representative of mobile water in the soil system (Landon et al., 1999).

Ammonia volatilization is the atmospheric loss of N to the atmosphere as ammonia gas (Knight Huckaby et al., 2012). Severity of ammonia volatilization varies with N source, soil pH, amount of irrigation water and other soil variables (Torello et al., 1983). High soil temperature and decreased soil water content will increase ammonia volatilization, while residue coverage decreases it (Clay et al., 1990). In turfgrass fertilization, surface applied urea can lose up to 60%

of that applied N through volatilization. This can be reduced by applying irrigation right after the urea is applied (Titko et al., 1987). In a study which examined prilled urea and sulfur-coated urea, turfgrass to which sulfur-coated was applied had less ammonia volatilization (2.3% of N applied) than prilled urea (10.3%) (Torello et al., 1983).

Denitrification is the gaseous loss of N as nitrous oxide gas (N_2O, NO) or N_2, due to anaerobic heterotrophic microbial activity (Mulvaney et al., 1997). It is highly related to irrigation and rainfall. One study on turf found that the loss of N in fertilizer through denitrification was 2.1 to 7.3% for N_2 and 0.4 to 3.9% for N_2O (Horgan et al., 2002). Turfed soils usually have a large amount of decomposable organic matter and are well-watered, which creates an anaerobic environment with a high denitrification rate (Carrow et al., 2001). A study with Kentucky bluegrass sod showed greatest denitrification in warm and saturated soils (> 30°C) (Mancino et al., 1988).

The opposite of N mineralization, immobilization of N happens when there is a high soil carbon to nitrogen ratio (C: N > 30:1). Bacteria need more N from organic biomass to support themselves, and inorganic soil N is removed from plant availability. This also results in less soil N available for plant uptake (Ferris et al., 1998). Research in a fertilized pasture found that more than 20% of applied N was fixed in microbial biomass through immobilization. However, immobilization decreased when N (dairy manner, in this study) was applied when soil temperatures were warmer (Ledgard et al., 1988).

Plant uptake also removes nitrogen from the soil system. In the study mentioned previously 31.1, 46.8 and 63.4% of applied N was taken up by plants, after each application of manure (Ledgard et al., 1988). Another study on ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.) and paspalum (*Paspalum dilatatum* Poir.), found that around 75% of applied N could be removed by plants in both “early” and “late” winter conditions (Ledgard et al., 1989). In N-limiting environments, plants may even take up dissolved organic N (Jones et al., 2005).

Ammonium (NH_4^+) can be fixed by clays, which then becomes unavailable to plants (Kowalenko and Cameron, 1976). Ammonium fixation usually occurs in 2:1 (silica to alumina layer) silicate clay minerals, specfically vermiculite and illite (McIntosh, 1962). Ammonium fixation is typically not a substantial issue in turfgrass soils.

Nitrogen Fertilizers

Even though there is N in soil to support plant growth, the amount is not sufficient for high quality and yield. As a result, N fertilizers are required for high quality turf (Bowman et al., 2002). In turfgrass, applied N fertilizers are often separated by their solubility and availability to turfgrass. In general, this includes soluble and immediately available N sources such as urea, or slow-release sources in which N is metered out over time (Gowans and Johnson, 1973). Turfgrass fertilizers usually have a higher content of N than phosphorus (P) or potassium (K) (Carrow et al., 2001).

a. Soluble

Water-soluble fertilizers, also known as quick-release fertilizers, will release nutrients immediately, and plants will respond rapidly after application (Mulvaney et al., 1997). These fertilizers can be dissolved in water and sprayed as a solution on turfgrass, which may help with N uptake. Soluble N fertilizers are also often cheaper than slow-release fertilizers (Bierman et al., 2015). A negative issue with quick-release fertilizers is that they may be more likely to cause to burn injury on turfgrass (Gowans and Johnson, 1973). Soluble N fertilizers, because they release all nutrients at once, may also pose a potential pollution risk, especially for N loss from leaching (Wong et al., 1998). In leaching from cool-season lawn turf, a higher NO_3-N leaching proportion from a quick-release fertilizer (ammonium nitrate) (16.8%) was reported, as compared to that from a slow-release fertilizer (polymer-coated sulfur-coated urea) (1.7%) or an organic product (0.6%) (Guillard and Kopp, 2004).

Urea is an N fertilizer with an N-P_2O_5-K_2O content of 46-0-0. Urea is formed by reacting ammonia with carbon dioxide at a high pressure. It can rapidly hydrolyze to the ammonium form. It is the most widely used nitrogen fertilizer (especially in developing countries), because of the high content of nitrogen (46%), low price, and ease of transportation (Bierman et al., 2015). Unlike ammonium sulfate, urea needs to be mixed into the soil, because it can easily convert into ammonium bicarbonate at the soil surface, which may then volatilize. Testing pasture surface soil samples, the hydrolysis rate of urea was reported to be up to 149 µg urea g $soil^{-1}$ h^{-1} in air-dried soils and 117 µg urea g $soil^{-1}$ h^{-1} in field moist soils (Reynolds et al., 1985).

Ammonium sulfate [$(NH_4)_2SO_4$] is another widely used N fertilizer for crop production, first developed and marketed as a fertilizer in the 1880’s. It has an N content of 21%, and an additional sulfur content of 24% (Zapp et al., 2000). It has a negligible volatilization rate (less than 1%), as compared with urea (17 to 59%), thus making it more acceptable for surface applications to turf or bare soils (Volk, 1959). Since it is soluble, it can also leach, as shown in some turfgrass studies (Brown et al., 1977).

Ammonium nitrate (NH_4NO_3) has an analysis of 34-0-0, with half the N from ammonium and half from nitrate. It was widely used for surface application because of its lack of ammonia volatility (Keller and Mengel, 1986). Ammonium nitrate can be produced from ammonia and nitric acid or formed during the decomposition of crude phosphate with nitric acid. The solubility of ammonium nitrate has a positive relationship with temperature above -20℃ (Zapp et al., 2000). Leaching research in 1996 reported that ammonium nitrate had a high leaching rate, up to 88% loss in sandy soils at 9 days after application (Wang and Alva, 1996).

However, ammonium nitrate fertilizer is now rarely used due to security concerns. On April 16, 1947, the ship Grand Camp exploded in the port of Texas City, Texas, because of ammonium nitrate fertilizer, which caught fire (Stephens, 1997). On April 19, 1995, 4000 pounds of ammonium nitrate fertilizers were made into a bomb by mixing with fuel oil. This terrorist act in Oklahoma City killed 168 people (Hogan et al., 1999). Ammonium nitrate has also been found to be toxic to frogs (*Rana temporaria*) even when the recommended rate of application was used (Oldham et al., 1997).

Calcium nitrate [$Ca(NO_3)_2$] is produced by dissolving limestone in nitric acid (Thiemann et al., 2012). It has been shown to reduce the severity of snow mold disease on *Agrostis* species more than other N sources (Tyson, 1936). Potassium nitrate (KNO_3) is used widely in vegetables, fruits and flower production. Because it is chloride-free, it can also be used on chloride-sensitive crops, such as potato and tobacco (Römheld and Kirkby, 2010). When spray-applied at a rate of 5 g N/m^2 to the foliage of perennial ryegrass (*Lolium perenne* L.), 40% of potassium nitrate was absorbed in 48 h (Bowman and Paul, 1992). Sodium nitrate ($NaNO_3$) was first mined from Chilean saltpeter, and was the most important inorganic N fertilizer before 1920 (Thiemann et al., 2012). Mining of sodium nitrate has created health issues, as there is concerns with the perchlorate anion, which might cause water pollution and damage people’s health (Urbansky et al., 2001).

b. Slow release

Slow release N fertilizers used on turfgrass can be separated into several groups according to different release mechanisms. This includes natural organic materials, synthetic organic materials and coated fertilizers (Carrow et al., 2001). Based on Hauck (1985) and Wilson (1988), controlled or slow-release fertilizers can be classified into the following four types:

1. Physically slow release

Physically slow release N fertilizers are created by covering the fertilizer prill (usually urea) with sulfur, resin, wax or some other coating (Shaviv, 2000). The most common coated slow-release fertilizers (SRFs) are sulfur- and polymer-coated urea (Blaylock, 2005). Sulfur-coated urea (SCU) was first produced in 1972. Sulfur-coated urea releases N by a combination of the biological oxidation of the S-coating combined with physical rupture or fracture of the coating (Blaylock, 2005). Sulfur-coated ureas for turfgrass use usually have a 25 to 35% dissolution rate, determined by a 7-d dissolution experiment in 38°C water (Carrow et al., 2001). Use of SCU will reduce ammonia volatilization. Nitrogen uptake efficiency has been shown to improve when SCU was the N sources, with an N recovery of 76%, as compared to 54% when urea was the N source (Allen et al., 1970). The sulfur-coating thickness determines the nutrient release rate of SCUs. However, this coating can easily be damaged. If this happens, SCUs will immediately release as soon as they contact water (Goertz, 1993).

An improved version of SCU, a polymer-coated SCU (PSCU) has been produced. These materials have some type of polymer coating (usually thermoplastic or resin) (Shaviv, 2000). Urea is released as the coating breaks down physically, and the materials have a more linear release rate compared to SCUs (Goertz, 1993). Other polymer-coated N fertilizers control nutrient release with semi-permeable coatings, occlusion, protein materials or other chemical forms (Trenkel, 2010). Unlike SCU materials, polymer-coated materials are less affected by microorganisms. These materials have been extensively used in non-agricultural markets, including turf, landscaping and horticulture (Shaviv, 2000). The polymer-coating is usually very thin, and acts like a sealant and delays water entry. A newer slow release N fertilizer combines SCU and PCU, creating a polymer and sulfur-coated material, typically abbreviated as PCSCU (Carrow et al., 2001).

Newest in the turfgrass marketplace are fertilizers with polymer coatings (Shaviv, 2000). Polyurethane, polyolefin and alkyd resin are used as materials in the various polymer coatings. Polymer-coated fertilizers usually have a thinner coating than SCU materials, as well as a higher N content (PCU: 39-44%, SCU: 32-38%) (Carrow et al., 2001). Water moves through the polymer coat, because the membrane is semipermeable, and N is slowly released through enlarged pores (Hauck, 1985). Coating thickness is negatively related with N content. Polymer-coated fertilizers with a thicker coating have a lower N content (Carrow, 1997). Compared with SCUs, PCUs are less affected by temperature and microbial activity (Salman et al., 1989). Polymer-coated fertilizers are widely used in professional turf (Hauck, 1985). They have been shown to significantly reduce N loss from leaching (Petrovic, 2004) and ammonium volatilization (LeMonte et al., 2016), while improving turf growth and quality. In a cool season turfgrass study application of PCU (Duration 45 CR®) significantly reduced ammonium volatilization (41-49%) as compared to urea. In the same study leaching losses of N were from 0-12% of N applied, significantly less than N leached from urea-treated plots (12-29% of N applied) (Petrovic, 2004).

2. Chemically slow release

Urea formaldehyde (UF) is the most popular and widely used slow release fertilizer that is chemically synthesized from urea (Trenkel, 2010). It consists of three types of N, cold water soluble N, and hot water soluble N and hot water insoluble N. The fertilizer is a mixture of unreacted urea, dimers and oligomers such as monomethylol urea dimethylol urea (DMU) and methylene urea produced by urea-formaldehyde reaction (Trenkel, 2010). The N release from UF depends on microbial activity, with reduced N release in low soil temperatures (Wilkinson, 1977). Based on a study with Merion Kentucky Bluegrass, spring-applied UF could produce and maintain high quality turf through the following summer and early fall. However, fall-applied UF could not keep quality turf at an acceptable level through the next spring (Wilkinson, 1977).

One specific type of urea formaldehyde is methylene urea (MU), which is used in agriculture, horticulture and forestry. Methylene ureas are classified by their different fractions water-insoluble N (WIN), which depend on the urea/ formaldehyde mole fraction of the urea-formaldehyde reaction. One example of a common turfgrass MU is Nutralene®. Nutralene® is produced with a U/F mole fraction of 1.9/1, with 35% of the N as water insoluble nitrigen. If the U/F mole fraction is increased to 2.0/1.0, Triaform, a circular liquid MU, is formed. Methylene ureas can be used to reduce ammonia volatilization, with ammonia losses less (6%) than that measured from urea (18%) (Huckaby et al., 2012).

Methylene urea is the first product formed in the urea-formaldehyde reaction. Other products are formed by increasing length of methylene urea polymers. These products are grouped into three fractions based on their solubility: 1) fraction I, cold water soluble (25℃), 2) fraction II, hot water soluble (100℃) and 3) fraction III, hot water insoluble. Longer chain polymers are more insoluble in water (even in hot water) (Carrow et al., 2001). The N release from UF fertilizers has several steps. Products in fraction I slowly release N at first, which is followed by N release from fraction II at around 3-4 months (Trenkel, 2010).

Isobutylidene Diurea (IBDU), which contains about 31% N, is also known as a chemically slow release fertilizer, and can either be used alone or mixed with other fertilizers (Carrow et al., 2001). Nitrogen release from IBDU is regulated by hydrolysis, particle size, and surface area (Blaylock, 2005). Unlike UF, IBDU is less dependent on microbial activity, and is also affected less by low temperature (Wilkinson, 1977). Isobutylidene Diurea is slow release due to its slow solubility in water, but its release rate increases with low pH, temperature and water content (Carrow et al., 2001). Isobutylidene diurea has been shown to be a slower-release N source, as compared with quick-release N fertilizers such as urea and NO_4NO_3 on turfgrass (Landschoot and Waddington, 1987)

3. True Organic Fertilizer

Nitrogen can also become available for plant use from organic N sources, such as animal manures, organic wastes and plant residues (Lamb et al., 2014). Organic fertilizers usually have a low N content, containing water-insoluble N, and release N slowly (Carrow et al., 2001). Since plants can only take up the inorganic form of N, these sources need to be transformed into either NH_4^+ or NO_3^- forms first (Lamb et al., 2014). Microbial activity plays the most important role to release inorganic N from organic materials (Carrow et al., 2001). One of the most popular organic N fertilizers used on turf is Milorganite®, which is an activated sewage sludge produced by the Milwaukee Sewerage Commission, a sludge compost. In a study with Milorganite®, only 32% of N from this source was taken up by turf in the first 2 years after application (Landschoot and Waddington, 1987). However, such materials are often shown to be benefical for the environment, having low rates of nitrate leaching, even under high application rates (Petrovic, 1990; Rieke and Ellis, 1974).

4. ‘Stabilized’ Nitrogen sources

Nitrification inhibitors and urease inhibitors are commonly called ‘stabilized N sources’ (Trenkel, 2010). When applied with urea fertilizers, these inhibitors can help to reduce NH_3 volatilization and NO_3^- leaching losses (Soares et al., 2012). Nitrification inhibitors are designed to slow the formation of NO_3^- in the soil by delaying the bacterial oxidation of NH_4^+ to NO_3^- (Subbarao et al., 2006). However, when soil has a high nutrient-holding capacity, such as the Catlin soil in one turf study, inhibitors were less effective (Spangengerg et al., 1986). Two common commercial nitrification inhibitors are dicyandiamide (DCD) and N-2,5-dichlorophenyl succinanilic acid (DCS). Dicyandiamide is applied in liquid manure form, while DCS is always mixed with ammonium sulphate (Trenkel, 2010). Application of dicyandiamide was reported to significantly increase yield (21%) and quality of grass in grazed pasture systems (Moir et al., 2007). Another registered nitrification inhibitor is nitrapyrin [2-chloro-6-(trichloromethyl)-pyridine]. Use of nitrapyrin reduced N_2O emissions by anhydrous ammonia by 63 (fall application) and 87 percent (Bremner et al., 1981).

Urease inhibitors can reduce volatilization losses by inhibiting the urease enzyme over a period of time. As a result, urease inhibitors slow down the speed of urea being hydrolyzed in the soil and ammonia volatilization, reducing atmospheric losses of ammonia gas (Trenkel, 2010). In urease inhibitor yield experiments on Kentucky bluegrass, phenylphosphorodiamidate (PPD), N-(n -butyl) thiophosphoric triamide (NBPT), and ammonium thiosulfate (ATS) increased clipping yield by 13.2%, 15.2% and 15% compared with the control group (urea alone) (Joo et al., 1991).

Methods to determine N release from coated N sources

Polymer-coated slow-release fertilizers (SRFs) have become widely used in agricultural, horticultural and turfgrass production (Medina et al., 2014). The polymer coating allows water to enter, creating different concentrations at two sides of the coating, and slowly releasing N (Carrow, 2001). However, the coating might be cracked or ruptured by excessing drying or mechanical damage, which would break the balance and increase the N release rate (Trenkel, 2010). To determine N release from coated sources, a variety of methods have been developed, both in the field and lab.

a. Field Methods to Evaluate N Release from Coated Sources

Many field techniques to measure N release from SRFs have been reported in the past few years. These field methods are useful, because the research environment is similar to field conditions, which makes results and conclusions practical (Carson and Ozores-Hampton, 2012). However, the methods are time consuming. Pot-in-pot and mesh bags are the two main methods used to evaluated N release (Simonne and Hutchinson, 2005; Wilson et al., 2009).

The pot-in-pot method, using two 20.3-cm-diameter plastic pots, nests two pots within each other with 1.5 cm spacers. This determines plant-available N release from PCUs by collecting leachate under a real field condition from the lower pot (Simonne and Hutchinson, 2005). The PCUs were mixed into soil in each pot, and nitrate and ammonium were analyzed from leachate samples every 7 days. Leachate samples were considered to include that N released from soil microbial activity, representing plant available N (Simonne and Hutchinson, 2005).

Used to determine N release and degradation of organic materials, mesh or cloth bags have long been used in many types of field work. In general, samples are placed in the bag and sealed. The bags and all samples are weighed so that nutrient loss and dry matter changes over time can be tracked (Ozores-Hampton and Carson, 2013). Bags may either be placed on the soil surface or incorporated into soil (Medina et al., 2008; Wilson et al., 2009). Bags are removed at various intervals (from days to months), weighed, and nutrient content determined. From those measurements degradation rates can be determined (Wilson et al., 2009).

The mesh bags were used to keep SRF samples together but still allow water movement (Carson and Ozores-Hampton, 2012). Wilson et al. (2009) used two types of mesh bags: 1) polypropylene mesh with 1.2 mm^2 hole openings and a 43% open area, and 2) weedblock landscape material with a hole size of around 0.07 mm^2 and an open area of 24%. In the end, N release rate was similar in the first 40 days after planting, regardless of bag types. While prills in the weedblock bags were typically cleaner than those in polypropylene mesh bags after removing from the potato hill, the hole size of the mesh bags did not have a significant influence on N release (Wilson et al., 2009).

b. Greenhouse Methods to Evaluate N Release from Coated Sources

Greenhouse methods create conditions that are more similar to a field environment, when compared with lab methods, but they require less space and cost. Column extraction methods and plastic bag methods are the two groups of greenhouse methods. However, due to the high variation of the results in different soils (Cahill et al., 2010), possibility of denitrification in a small closed system, and low N recovery rate (<60%) in plastic bag methods (Sartain et al., 2004), column extraction methods are more widely used as greenhouse methods.

In the column extraction methods, columns are filled with media, such as washed sand. Often, a carbon source, such as citric acid, is added. Slow-release fertilizers are placed 0.4 to 2 inches below media surface. Different frequencies and volumes of water can be used to cause N release (Carson and Ozores-Hampton, 2012). In a polymer-coated fertilizer study, the sand columns were leached at two different temperatures (30 and 40°C) with deionized water 3 times per week until 90% of N release occurred. In one such study N was released more quickly as temperature increased (Huett and Gogel, 2000).

c. Lab Methods to Evaluate N Release from Coated Sources

Methods that evaluate N loss via field methods are affected by environmental factors, such as temperature, pH or soil moisture (Trenkel, 2010). They also require more time and money, as well as a larger space. Laboratory methods, in comparison, create a more stable environment for slow-release fertilizer incubation, as compared with field methods. If properly calibrated, they may also predict N release over a shorter time period.

Most temperature-controlled N incubation methods have been developed in the past decade. In one method, SRFs were mixed into temperature-controlled water. One standard method was to keep water temperature at 25C, and use incubation times based on either the N release rate (to 100% of N release) or time (4-month). The method was then improved by increasing the incubation temperature to 25 and 65C, with a 0.2% citric acid extraction solution added. This method allowed determination of N release within 0 to 20 h after incubation (Sartain et al., 2004). A similar experiment was also performed by Medina et al (2009). In this experiment, four temperature treatments were used: 1) 2 h at 25C, 2) 2 h at 40C, 3) 20 h at 50C, and 4) 50 h at 60C. The N release curve showed a positive relationship between temperature and N release. These two experiments successfully used this accelerated temperature-controlled incubation method for up to 74 hours (Medina et al., 2009; Sartain et al., 2004) successfully calibrating N release of coated products. By testing the N release rate at four temperatures (50C, 60C, 70C, 80C), significant differences were found due to temperature. The rate of N release at 80C was significantly higher than that at 25C, and it was found that the 4-month long release test (at 25C) could be replaced by a 16- 24 h release test (at 80C) (Dai et al., 2008).

Traffic Simulators

In an athletic turfgrass field, the playing surface can tolerate more than seven times the body weight of athletes (Cockerham et al., 1990; Gatt et al., 1996; Henderson et al., 2005). To test how athletic field traffic damages turfgrass and the field, traffic simulation devices, such as the Brinkman traffic simulator (BTS) (Cockerham and Brinkman, 1989), the Cady traffic simulator (CTS) (Henderson et al., 2005) and the Baldree traffic simulator (Kowalewski et al., 2015), were developed. Traffic simulators simulate realistic traffic and create wear injury (Trenholm et al., 1999) and soil compaction (Cockerham et al., 1990) by using different rollers (cleated or smooth) with different speeds (Henderson et al., 2005). The BTS was used more frequently before 2005, as it created uniform and reproducible wear. The simulator utilized rubber-wheels, rollers and studded drums, which simulated turfgrass injury successfully (Cockerham and Brinkman, 1989; Henderson et al., 2005; Vanini et al., 2007). In 2005, another traffic simulator known as the Cady traffic simulator (CTS), which produced dynamic forces on the turfgrass surface, was developed. The CTS was a modified walk-behind core cultivation unit, with four "foot" attracted core heads. The three-directional dynamic forces were produced by the "foot" alternately striking the field (Henderson et al., 2005). Compared with the BTS, the CTS had higher stress on both peak compressive stress and peak net shear stress. The CTS produced 30 times higher average compressive stress and 15 times higher average net shear stress in the forward direction, and 5 times higher average compressive stress and 4 times higher average net shear stress in the reverse direction than the BTS (Henderson et al., 2005). However, the CTS still had the problem of lacking the durability compared with the BTS (Kowalewski et al., 2015). To solve this problem, in 2013, a new simulator called the Baldree traffic simulator, which used a modified Ryan GA 30, was developed. The modified Ryan GA 30 was a riding aerification unit, which had fabricated, spring loaded steel plate feet studded with screw in cleats. To apply traffic this unit had a speed of 0.35 m s^{-1} in both forward and backward directions. The Baldree traffic simulator increased the number of cleat marks to 1129 per pass, which equaled 2 football games. This helped to apply heavy traffic on research fields with a minimum number of passes (Kowalewski et al., 2013).

Measuring the Extent of Damage to PCU coatings by Traffic or Handling

Polymer-coated fertilizers are widely used in agricultural, horticultural and turf grass production. The polymer-coatings were formulated to synchronize N release over a given period of time. Thus, their efficiency depends on having intact coatings (Bierman et al., 2015). When not damaged, seedling growth was unaffected by PCU coatings (Qin et al., 2014). However, PCU fertilizers may be damaged at the retail point, during implement loading or through field application (Bierman et al., 2015). In a study of PCU fertilizer coating integrity by implement loading, several levels were created through laboratory simulation. After simulated handling, PCUs were separated into 9 levels based on proportion of N release after 7d in 23C water. Fertilizers that had been damaged in handling affected seedling stands of winter wheat and canola, with stand reductions of 30 to 18% when fertilized with the damaged fertilizers (Beres et al., 2012).

Since PCU coatings can be damaged under many conditions, tests are necessary to determine N release, which can provide application information to dealers, consultants, researchers and growers (Bierman et al., 2015). Even though many field and lab methods are available, they usually take a few weeks or months (Carson and Ozores-Hampton, 2012). Rapid coating damage tests still need to be developed.

One study used 50 mL of water, to which was added four drops of red food coloring, mixed with 100 PCU prills. The proportion of dyed prills was considered as damaged percentage (Parish, 2001a; Parish, 2001b). This method was rapid and easy, but could not determine a percent N release. Another study determining the N release rate of PCU used 23C water. Ten pre-weighed prills were put into 500 mL of water and recovered after 6h, 2, 4, 6, 8, 10 and 12 d. Recovered prills were dried at 65C, and weight losses were calculated as the percentage of urea released (Zhang et al., 2000). Based on the N release percentage curves of two PCUs in the study, the N release from prills could be detected at the second day after being put into water.

The definition of a slow-release fertilizer is that there should be no more than 15% nutrient release during a 24 hour incubation period (Trenkel, 2010). A 24-hour water lab immersion test was developed to measure prill damage. In this method, 3 to 4 g of PCUs were first placed in 400 mL distilled water with 15 seconds of stirring, and were then removed from the water after 24 h by sieving through a 1.2-mm^2 mesh polypropylene screen. After air-drying and drying at 40C for 24 h, the weight loss percentage was determined (Bierman et al., 2015; Wilson et al., 2009). In a 2 year experiment by Bierman et al. (2015), the control group was PCUs collected directly from the dealer, with treated fertilizers collected from the deflector plates of a pneumatic fertilizer spreader. Damage on prills was found, with the proportion of N release greater than 30% in the 24-h water immersion test. This damage led to higher plant uptake of N, and also posed a hazard for leaching (Bierman et al., 2015).

Even though methods to determine N release from coated fertilizers have been developed, field studies in turfgrass are still lacking. Other than being damaged during retail points, implement loading, and field application, PCUs may also be damaged by human traffic, such as by football players' cleats on football fields after being applied to turfgrass fields. Many studies have been done to test the surface-shoe interaction with sports injuries in the American football on different turf fields (Nigg and Segesser, 1988). For example, one study that tested in-shoe foot loading reported that the central forefoot created around 646.6 kPa pressure on turf

(Ford et al., 2006). Such forces could possibly damage fertilizer prills. However, such work has not yet been completed.

Objectives

Therefore, the objective of this study was to: 1) determine prill damage on different N sources using artificial traffic, and, 2) evaluate prill damage and possible N release as affected by real-life foot traffic.

II. MATERIALS AND METHODS

Experiments were performed at two locations: 1) the Auburn University (AU) Turfgrass Research Unit, and 2) the AU Practice Fields. At both locations the grass type was ‘Tifway’ hybrid bermudagrass (*Cynodon dactylon* × *C. transvaalensis* Pers. L.) with a 4.0 cm mowing height. Four experiments were conducted, all designed to evaluate N loss from various coated prills as affected by foot traffic. For all experiments, the various N sources (listed in Table 1) were applied to four replicate plots, with each plot 0.3 × 0.5 m in size. All experiments were a 2 by ‘x’ factorial design of traffic (traffic or none) and ‘x’ fertilizer sources (see Table 1 for specific sources). The experiments were arranged in a split-plot design with main plot of traffic and split- plot of N source.

In experiment 1 and 3, the Cady traffic simulator was used to apply artificial athletic traffic. For our studies, a Jacobsen Greensaire® 24 (GA-24) walk-behind aerator (Commercial Grounds Care Inc., Johnson Creek, WI) was modified as the traffic simulator. This machine was a modified core aerator, with the aerator tines removed and replaced with ‘feet’ made of tires with bolts attached (Fig 1). These feet strike the turf field alternately with the machine moving, creating three-direction dynamic forces simulating realistic human traffic. The machine was passed over the treated plots three times for each treatment in forward direction. Three passes of the CTS were intended to created cleat marks which equaled to two football games (Henderson et al., 2005, Kowalewski et al., 2015).

A total of four separate experiments were conducted. Specific experiments were:

Experiment 1

Experiment 1 was located at the Auburn University Turf Research Unit. Fertilizers were handed applying to specific plots on 22 Sep. 2015, 21 Oct. 2015 and 30 Oct. 2015. Different areas of turf were used for each experiment. This experiment was repeated three times, with each experiment lasting 7 days. The specific experiment was a factorial combination of 6 fertilizer sources (Table 1) and two levels of traffic (traffic and none), with traffic applied just prior to sampling, at days 1, 3 and 7. First traffic was applied 24 hr after fertilizer application. Fertilizers were hand-applied to the turfgrass, and no additional incorporation was applied, including no irrigation. The research plots were not mowed during this week-long period.

Experiment 2

Experiment 2 was located at the AU Practice Fields. This experiment also was repeated three times, on 9 Nov. 2015, 30 Nov. 2015 and 19 Apr. 2016, with treatments of fertilizer source (Table 1) and foot traffic, and no foot traffic. Different areas of turf were used for each experiment. In this experiment foot traffic was created by real human traffic, applied via foot traffic from the lacrosse team. Non-trafficked plots were located in a small corner area of field, and marked so that traffic did not occur there. Prills were collected once, after 7 days.

Experiment 3

Experiment 3 was located at the Auburn University Turf Research Unit. This experiment used the traffic machine to apply artificial traffic on selected treatments, with a starting date on 7 Jun. 2016. Traffic equivalent to two high school football games was applied 24-hr after fertilizers were applied. No additional traffic was applied for the length of the experiment. Because of the 9-week experiment all plots were mowed two days per week at 4.0 cm. This experiment was conducted for 63 days (9 weeks). The experiment was arranged as a factorial combination of 4 fertilizer sources (Table 1) and two levels of traffic (traffic and none), with traffic applied one time before fertilizers were weighed and put into mesh bags. Samples were collected at 1, 3, 5, 7, and 9 weeks after application. Specific details on N release from the mesh bags is supplied later in this section.

Experiment 4

Experiment 4 was located at the Auburn University Turf Research Unit, with treatments of fertilizer source (Table 1) and foot traffic, starting on 24 Jul. 2016. In this experiment, foot traffic was created by real human traffic, applied by 4 students running across and doing high intensity exercise across the plot areas to simulate two football games, wearing football cleats. Traffic was only applied one time, prior to the start of the 9 week experiment. Samples were collected at 1, 3, 5 and 7 weeks after application.

When natural traffic was applied it was done so at a rate equivalent to two football games. To develop this typical level of foot traffic three randomly selected football (American-style) games were viewed from YouTube® libraries. Four students watched the games, and each watched a pre-selected 3 x 3-m area of the field for ten minutes of each quarter. Each time that a foot was planted in that area it was counted, leading to a total number of footfalls per area per minute. Initial counts were averaged over area and all games, and results compared. Footfalls per area were greatest in the center of the field, and this was used as our ‘worst-case’ scenario for applying real-life traffic to plots at the Turfgrass Research Unit. Trafficked plots were run across by the students to equal that counted from the observations of real football games.

Nitrogen release from prills was measured, as follows:

For experiments 1 and 2 fertilizer prill damage was assessed using the water dissolution method as described by Wilson et al. (2009):

For this method, 20 prills were carefully handpicked from each plot, and placed into a plastic bag for removal to the lab. There a 24-h water immersion test was used (Bierman et al., 2015). First, fertilizer samples were weighed, and then put into 400 mL of distilled water for a 24h incubation. Samples were then filtered from the water and weighed again, after being dried in a forced air oven at 40C for 24 h (Wilson et al., 2009).

Mesh bags were used in experiment 3 and 4. For these experiments a known weight of prills were hand-harvested from respective plots after application of traffic. Prills were inserted into 5 x 4 cm mesh bags which were then sealed to prevent prill loss. Bags (1 bag per sampling time) were then inserted into a 6-cm deep slit cut into each plot, ensuring soil/prill contact. One bag was removed at week 1, 3, 5, 7 and 9 from each plot, and dried weight determined.

Nitrogen loss from prills was calculated using the following equation (Bierman et al., 2015):

$$F_c = F_i - \left[\frac{F_i * (\%N_{PCU})}{\%N_{urea}}\right] \qquad \text{(Eq. 1)}$$

Where:

F_c= the weight of the polymer coating in grams.
F_i= initial amount of PCU in the sample.
$\%N_{PCU}$= percentage of N in the PCU product.
$\%N_{urea}$= percentage of N in uncoated urea.

Percent released nitrogen (%NR) for each sample was calculated out of the percentage of weight loss, using the following equation (Bierman et al., 2015):

$$\%NR_w = \left[1 - \left(\frac{F_s - F_c}{F_i - F_c}\right)\right] * 100 \qquad \text{(Eq. 2)}$$

$\%NR_w$= the percentage of N release by weight.
F_s= the weight of the PCU on the sampling date.

Data from all four experiments were analyzed using SAS 9.4 (SAS Institute). PROC GLM were used to test the ANOVA between repeats of each experiment. Means of N release proportion were analyzed using PROC MEANS, and treatment effects were compared at the 0.05 significance level using least-square means. Plots were produced by PROC GPLOT.

III. RESULTS AND DISCUSSION

Experiment 1

Similar results in N release were observed for all Runs on day 1 and day 7 (Table 2). On day 3 there was a slight significant difference in N release due to Run, likely a factor of different soil temperature over the month-long period over which the experiment was run. Since the majority of the Results were unaffected by Run we have chosen to show all results averaged over Run, for Experiment 1. Since the interaction of N source and traffic was significant, data were shown as a table of interaction (Table 3).

In experiment 1, N release from trafficked prills was often greater than that from prills that did not receive traffic. In general, prills that had the lowest coating weight were most likely to be damaged. This corresponded to prills with the quickest release times (Duration CR 45 and 90 day, and Polymer-Coated, SCU products) (Table1; Table 3). Significantly more N was released from the trafficked Duration CR 45 day material over the 7 day sampling period, and this was found at every sampling date.

Nitrogen release from polymer-coated materials with the thickest coating (Duration CR 180 day material) was never affected by traffic (Table 3). Overall, N release from trafficked prills was greatest in fertilizers with a rapid N release (thinner coating) than in those with a thicker coating (Figs 2-4).

The definition of a slow-release fertilizer is that there should be no more than 15% nutrient release during a 24 hour incubation period (Trenkel, 2010). Prill coating can be considered as being damaged when percent N release exceeds 15% (Bierman et al., 2015). Based on this, significant prill damage was observed in day 1 in the SCU XCU N source and PolyPlus source. However, N loss exceeded 15% in the non-trafficked PolyPlus material, too. Similar results were observed at 3 and 7 days after fertilizer application (Table 3).

Experiment 2

For experiment 2, there was not a difference in measured N release as affected by natural foot traffic (Table 4). There was no significant N source × traffic interaction as well ($\alpha > 0.05$), and so data over every Run will be averaged and discussed (Table 4).

In experiment 2, there was no effect of traffic on prill damage, as measured by N release (Table 5). Polymer-coated prills having lowest coating weight were more likely to be damaged (Duration CR 45 day and Polymer-coated, SCU products), compared with those having thicker coatings (Duration 180 day) (Table 4). Overall four PCUs, materials with thicker coatings also had lower N loss at the sampling date (Fig 5), regardless of traffic.

Experiment 3

In experiment 3, there was no significant N source × traffic interaction observed (Table 6). Nitrogen release increased during the 9 weeks of experiment over all four Duration CR materials (Table 7). Differences in N release due to the one-time application of traffic were found in some sources, at different sampling times. For example, traffic created greater N loss at week 5 in the 45-day material, at week 3 in the 90-day material, and in week 1 of the 120-day material. Traffic had no effect on N release on N release from the 180-day material (Table 7).

There was a general trend for greater N release earlier in the study from materials with thinner coatings (Figs 6-10). This was largely not affected by traffic, but instead by the thickness of the fertilizer coating only. Simply, materials with a thinner coating released more N quickly as compared to the thicker coated materials (Figs 11-12), regardless of traffic.

Experiment 4

In experiment 4, no interaction was found on N source × traffic (Table 8). Nitrogen release percentages increased in all four PCUs in both treatments over time during the 7 weeks of experiment. The highest percent N release occurred from the Duration 45-day product and the lowest occurred from Duration 180-day product (Table 9).

Real foot traffic (only one day of application) sometimes affected N release (Figure 13), but only early in the experiment. Nitrogen release was slower in N sources with a thicker coating as would be expected (Figs 14-15). In general, N release was unaffected by the presence of natural foot traffic (Figs 16-18), especially in later weeks.

In general, the use of artificial traffic affected the integrity of the fertilizer prill, but only in prills with a more rapid release, and thus a thinner coating. Others have found similar damage in thinner coated fertilizer products (Bierman et al., 2015). In that study the effects of fertilizer handling and application were evaluated, and not foot traffic. The fertilizers used in this study were supplied directly from the processing plant, and thus while some handling had occurred our products had not gone through mixers or spreaders.

When real traffic was applied the effects of traffic were either not present or very slight, and not present for any extended period of time. Our hypothesis is that the extent of foot traffic applied in our studies was insufficient to impact the integrity of any great number of prills. The traffic exerted at the AU Practice fields was from lacrosse practice, and observations of out treated areas clearly showed that traffic had been imparted on the plots (excluding the no-traffic area). Additionally, communication with the coach affirmed that the team had practiced three times in the week that fertilizer prills were present.

Regardless, it appears that the actual chances of a cleat hitting, and possibly damaging a prill, are not large, and in a typical fertilization scheme the likelihood of a cleat squarely encountering a fertilizer prill is slight. At a typical N fertilization rate of 4.9 g N m^{-2} a fertilizer prill (SGN 220) would be placed about every 6 to 10-cm, a wide enough spacing that damage would not be a concern. However, given the damage that was observed when intense traffic was applied (via the artificial traffic) it should be noted that a general warning to not apply coated fertilizers immediately before a large-scale athletic event (such as a soccer tournament) would be advised.

Because of the difficulty in harvesting prills for extended periods of time (weeks) additional research is needed to completely assess the potential damage to prills when traffic is continually applied. Our work did not assess what could happen to the long-term release of N when those prills receive traffic over weeks. We only studied long-term release as affected by traffic within a few days of application. Since we did observe some damage when that traffic was applied (artificial traffic only) the potential effects of long-term traffic should also be studied. Fertilizer prills that are engorged with water may be more prone to damage, or, conversely, such prills may become more incorporated with thatch and soil over time, thus protecting them from damage. Although such work is needed studies will need to be designed so that prills can easily be recovered over a period of weeks, an issue when in –play fields are a part of the research.

IV. CONCLUSION

In the 7-day short term traffic experiments, the presence of artificial traffic was found to affect prill integrity, while the natural foot traffic did not. Artificial traffic damaged the prills, releasing N, while natural traffic did not. In the long term studies similar results were observed. Materials with a thinner coating were more likely to be damaged. It appears that natural foot traffic is not likely to damage coated fertilizer prills, at least when traffic is at a reasonable level.

REFERENCES

Allen, M.B. and Arnon, D.J. 1955. Studies on nitrogen-fixing blue-green algae. I. Growth and nitrogen-fixation by Anabaena cylindrica Lemn. Plant Physiol. 30:366–372.

Allen, S.E., Hunt, C.M. and Terman, G.L. 1970. Nitrogen release from sulfur-coated urea, as affected by coating weight. Agron. J. 63:529–533.

Allos, H.F. and Bartholomew, W. V. 1955. Effect of available nitrogen on symbiotic fixation. Proc. Soil Sci. Soc. Am. 19:182–184.

Barton, L. and Colmer, T.D. 2006. Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. Agric. Water Mngt. 80:160–175.

Basak, M.N., Sen, S.K. and Bhattacharjee, P.K. 1962. Effects of high nitrogen fertilization and lodging on rice yield. Agron. J. 54:477-480.

Beres, B. L., McKenzie, R. H., Dowbenko, R. E., Badea, C. V. and Spaner, D. M. 2012. Does handling physically alter the coating integrity of ESN urea fertilizer? Agron. J. 104:1149-1159.

Bi, G., Scagel, C.F. and Harkess, R. 2008. Rate of nitrogen fertigation during vegetative growth and spray applications of urea in the fall alters growth and flowering of florists' hydrangeas. HortScience 43:472–477.

Bierman, P.M., Crants, J.E. and Rosen, C.J. 2015. Evaluation of a quick test to assess polymer-coated urea prill damage. Agron. J. 107:2381–2390.

Blaylock, A. D., Kaufmann, J. and Dowbenko, R. D. 2005. Nitrogen fertilizer technologies. Western Nutrient Management Conference 6:8-13.

Bowman, D.C., Cherney, C.T. and Rufty, T.W. 2002. Fate and transport of nitrogen applied to six warm-season turfgrasses. Crop Sci. 42:833–841.

Bowman, D.C. and Paul, J.L. 1992. Foliar absorption of urea, ammonium, and nitrate by perennial ryegrass turf. J. Am. Soc. Hort. Sci. 117:75–79.

Bremner, J. M. 1965. Inorganic forms of nitrogen. Methods of soil analysis. Part 2. Chemical and microbiological properties, Agronomy Monograph 9.2, 1965. Agron. Soil Sci. Soc. 1179-1237.

Bremner, J. M., Breitenbeck, G. A. and Blackmer, A. M. 1981. Effect of nitrapyrin on emission of nitrous oxide from soil fertilized with anhydrous ammonia. Geophysical Research Letters 8:353-356.

Brown, K. W., Duble, R. L., and Thomas, J. C. 1977. Influence of management and season on fate of N applied to golf greens. Agron. J. 69:667-671.

Cahill, S., Osmond, D. and Israel, D. 2010. Nitrogen release from coated urea fertilizers in different soils. Communications in Soil Science and Plant Analysis 41:1245-1256.

Carrow, R.N. 1997. Turfgrass response to slow-release nitrogen fertilizers. Agron. J. 89:491–496.

Carrow, R. N., Waddington, D. V., and Rieke, P. E. 2001. Turfgrass soil fertility and chemical problems: Assessment and problems. Ann Arbor Press, Chelsea, MI.

Carson, L.C. and Ozores-Hampton, M. 2012. Methods for determining nitrogen release from controlled-release fertilizers used for vegetable production. HortTechnology 22:20–24.

Clarholm, M, Popovic, B., Rosswall, T., Söderström, Bengt L. U., Sohlenius, B., Staaf, H. and Wiren, A. 1981. Biological aspects of nitrogen mineralization in humus from a pine forest podsol incubated under different moisture and temperature conditions. Oikos 37:137–145.

Clay, D.E., Malzer, G.L. and Anderson, J.L. 1990. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. Soil. Sci. Soc. Am. J. 54:263.

Cockerham, S. T. and Brinkman, D. J. 1989. A simulator for cleated-shoe sports traffic on turfgrass research plots. California Turfgrass Culture 39: 9-10.

Cockerham, S. T., Gibeault, V. A., Van Dam, J. and Leonard, M. K. 1990. Tolerance of several cool-season turfgrasses to simulated sports traffic. In Natural and Artificial Playing Fields: Characteristics and Safety Features. ASTM International:85-95.

Daane, K., Johnson, R., Michailides, T., Crisosto, C., Dlott, J., Ramirez, H., Yokota, K. and Morgan, D. 1995. Excess nitrogen raises nectarine susceptibility to disease and insects. California Agriculture 49:13-18.

Dai, J. J., Fan, X. L., Yu, J. G., Fang, L. I. U., and Zhang, Q. 2008. Study on the rapid method to predict longevity of controlled release fertilizer coated by water soluble resin. Agricultural Sciences in China 7:1127–1132.

Ferris, H., Venette R.C., van der Meulen H.R. and Lau S.S. 1998. Nitrogen mineralization by bacterial-feeding nematodes: Verification and measurement. Plant and Soil 203:159–171.

Fierer, N., Leff, J. W., Adams, B. J., Nielsen, U. N., Bates, S. T., Lauber, C. L., Owens, S., Gibert, J. A., Wall, D. H. and Caporaso, J. G. 2012. Cross-biome metagenomic analyses of soil microbial communities and their functional attributes. Proceedings of the National Academy of Sciences 109:213.

Ford, K. R., Manson, N. A., Evans, B. J., Myer, G. D., Gwin, R. C., Heidt, R. S. and Hewett, T. E. 2006. Comparison of in-shoe foot loading patterns on natural grass and synthetic turf. Journal of Science and Medicine in Sport 9:433-440.

Gatt Jr, C. J., Hosea, T. M., Palumbo, R. C., and Zawadsky, J. P. 1996. Impact loading of the lumbar spine during football blocking. The American journal of sports medicine 25:317-321.

Goertz, H.M. 1993. Technology developments in coated fertilizers. Proceedings: Dahlia Greidinger Memorial International Workshop on Controlled/Slow Release Fertilizers, Technion-Israel Institute of Technology, Haifa, 7-12.

Golembiewski, R.C. and Danneberger, T.K. 1998. Dollar spot severity as influenced by trinexapac-ethyl, creeping bentgrass cultivar, and nitrogen fertility. Agron. J., 90: 466–470.

Gowans, K.D. and Johnson, E.J. 1973. Nitrogen source in relation to turfgrass establishment in sand. California Turfgrass Culture 23:9–16.

Gross, C.M., Aangle, J.S. and Welterlen, M.S. 1990. Nutrient and sediment losses from turfgrass. J. Environ. Qual. 19:663–668.

Guillard, K. and Kopp, K.L. 2004. Nitrogen fertilizer form and associated nitrate leaching from cool-season lawn turf. J. Environ. Qual. 33:1822–1827.

Hauck, R. D. 1985. Slow-release and bioinhibitor-amended nitrogen fertilizers. Fertilizer technology and use. 3rd Ed.:293-322.

Henderson, J. J., Lanovaz, J. L., Rogers, J. N., Sorochan, J. C. and Vanini, J. T. 2005. A new apparatus to simulate athletic field traffic: The Cady traffic simulator. Agron. J. 97:1153–1157.

Hill, R.D., Rinker, R.G. and Wilson, H.D. 1980. Atmospheric nitrogen-fixation by lightning. Journal of Atmospheric Sciences 37:179–192.

Hogan, D. E., Waeckerle, J. F., Dire, D. J. and Lillibridge, S. R. 1999. Emergency department impact of the Oklahoma City terrorist bombing. Annals of emergency medicine 34:160-167.

Horgan, B.P., Branham, B.E. and Mulvaney, R.L. 2002. Direct measurement of denitrification using 15N-labeled fertilizer applied to turfgrass. Crop Sci. 42:1602–1610.

Huber, D.M. and Watson, R.D. 1974. Nitrogen form and plant disease. J. Chem. Inf. Model. 53:1689–1699.

Huckaby E. C., Wood C. W. and Guertal E. A. 2012. Nitrogen source effects on ammonia volatilization from warm-season sod. Crop Sco. 52:1379-1384.

Huett, D. O. and Gogel, B. J. 2000. Longevities and nitrogen, phosphorus, and potassium release patterns of polymer-coated controlled-release fertilizers at 30°C and 40°C Communications in Soil Science and Plant Analysis 31:959-973.

Jones, D.L., Healey, J. R., Willett, V. B., Farrar, J. F., and Hodge, A. 2005. Dissolved organic nitrogen uptake by plants - an important N uptake pathway? Soil Biology and Biochemistry 37:413–423.

Joo, Y.K., Christians, N.E. and Bremner, J.M. 1991. Turf response to urease inhibitors and cationic materials applied in combination with urea. HortScience 26:537–539.

Keller, G.D. and Mengel, D.B. 1986. Ammonia volatilization from nitrogen fertilizers surface applied to no-till corn. Soil Sci. Soc. Am. J. 50:1060.

Knight-Huckaby, E.C., Wood, C.W. and Guertal, E.A. 2012. Nitrogen source effects on ammonia volatilization from warm-season sod. Crop Sci. 52:1379–1384.

Kole, M.M., Page, W.J. and Altosaar, I. 1988. Distribution of *Azotobacter* in eastern Canadian soils and in association with plant rhizospheres. Canadian Journal of Microbiology 34:815–817.

Kowalenko, C. G., and Cameron, D. R. 1976. Nitrogen transformations in an incubated soil as affected by combinations of moisture content and temperature and adsorption-fixation of ammonium. Can. J. Soil Sci. 56:63-70.

Kowalewski, A. R., Schwartz, B. M., Grimshaw, A. L., Sullivan, D. G., Peake, J. B., Green, T. O., Rogers, J.N., Kaiser, L.J. and Clayton, H. M. 2015. Biophysical effects and ground force of the Baldree traffic simulator. Crop Sci. 53:2239–2244.

Ladha, J. K., Reddy, C. K., Padre, A. T., and van Kessel, C. 2011. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. J. Environ. Qual. 40:1756-1766.

Lamb, J.A., Fernandez, F.G. and Kaiser, D.E., 2014. Understanding nitrogen in soils. University of Minnesota Extension, (Revised):1–5.

Landon, M. K., Delin, G. N., Komor, S. C., and Regan, C. P. 1999. Comparison of the stable-isotopic composition of soil water collected from suction lysimeters, wick samplers, and cores in a sandy unsaturated zone. J. Hydrology 224:45–54.

Landschoot, P.J. and Waddington, D. V. 1987. Response of turfgrass to various nitrogen sources. Soil Sci. Soc. Am. J. 51:225-230.

Ledgard, S.F., Brier, G.J. and Sarathchandra, S.U. 1989. Plant uptake and microbial immobilization of ^{15}N-labelled ammonium applied to grass-clover pasture—influence of simulated winter temperature and time of application. Soil Biol. Biochem. 21:667–670.

Ledgard, S.F., Steele, K.W. and Feyter, C. 1988. Influence of time of application on the fate of ^{15}N-labelled urea applied to dairy pasture. New Zealand Journal of Agricultural Research 31:87–91.

LeMonte, J. J., Jolley, V. D., Summerhays, J. S., Terry, R. E., and Hopkins, B. G. 2016. Polymer coated urea in turfgrass maintains vigor and mitigates nitrogen's environmental impacts. Plos One 11:1–13.

Li, Y., Wang, J., Pan, F., Chapman, S. J., and Yao, H. 2016. Soil nitrogen availability alters rhizodeposition carbon flux into the soil microbial community. J. Soils and Sediments 16:1472–1480.

Madani, A. and Oveysi, M., 2015. Fiber quality and yield response of cotton to nitrogen supply. International Conference on Chemical, Food and Environment Engineering. (ICCFEE15):2009–2011.

Mancino, C.F., Torello, W.A. and Wehner, D.J. 1988. Denitrification losses from Kentucky bluegrass sod. Agron. J. 80:148–153.

McIntosh, T. H. 1962. Fixation of added ammonium by the clay and organic fractions of soil. Ph. D. thesis Ames, Iowa State University.

Medina, L., Sartain, J. B., Obreza, T. A., Hall, W. L., and Thiex, N. J. 2014. Optimization and validation of an accelerated laboratory extraction method to estimate nitrogen release patterns of slow- and controlled-release fertilizers. Journal of AOAC International 97:661–676.

Medina, L. C., Obreza, T. A., Sartain, J. B. and Rouse, R. E. 2008. Nitrogen release patterns of a mixed controlled-release fertilizer and its components. HortTechnology 18:475-480.

Medina, L.C., Sartain, J.B. and Obreza, T.A. 2009. Estimation of release properties of slow-release fertilizer materials. HortTechnology 19:3–15.

Moir, J.L., Cameron, K.C. and Di, H.J. 2007. Effects of the nitrification inhibitor dicyandiamide on soil mineral N, pasture yield, nutrient uptake and pasture quality in a grazed pasture system. Soil Use Mngt. 23:111–120.

Mulvaney, R.L., Khan, S.A. and Mulvaney, C.S. 1997. Nitrogen fertilizers promote denitrification. Biol. Fert. Soils. 24:211–220.

Muruganandam, S., Israel, D.W. and Robarge, W.P. 2009. Activities of nitrogen-mineralization enzymes associated with soil aggregate size fractions of three tillage systems. Soil Sci. Soc. Am. J. 73:751–759.

Mylona, P., Pawlowski, K. and Bisseling, T. 1995. Symbiotic nitrogen fixation. Plant Cell 7:869–885.

Nigg, B. M., and Segesser, B. 1988. The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. Sports medicine 5:375-385.

Oldham, R.S., Latham, D. M., Hilton-Brown, D., Towns, M., Cooke, A. S., and Burn, A. 1997. The effect of ammonium nitrate fertiliser on frog (*Rana temporaria*) survival. Ag. Ecosyst. Environ. 61:69–74.

Ozores-Hampton M. and Carson L. C. 2013. Methods for measuring nitrogen release from controlled-release fertilizer used for vegetable production. University of Florida HS1227:1-7. http://edis.ifas.ufl.edu/hs1227.

Parish, R. L. 2001a. Spreader damage to encapsulated controlled-release fertilizer granules. Applied Engineering in Agriculture 17:457.

Parish, R. L. 2001b. Effect of coating thickness on spreader damage to encapsulated controlled-release fertilizer granules. Applied Engineering in Agriculture 17:459-460.

Petrovic, A.M. 1990. Fate of nitrogenous fertilizers applied to turfgrass. J. of Environ. Qual. 19:1-14.

Petrovic, A.M. 2004. Nitrogen source and timing impact on nitrate leaching from turf. Acta Horticulturae 661:427–432

Peyraud, J.L. and Astigarraga, L. 1998. Review of the effect of nitrogen fertilization on the chemical composition, intake, digestion and nutritive value of fresh herbage: Consequences on animal nutrition and N balance. Animal Feed Sci. Tech. 72:235–259.

Qin, S., Stevenson, F. C., McKenzie, R. H., and Beres, B. L. 2014. Seed safety limits for cereals and canola using seed-placed ESN urea fertilizer. Agron. J. 106:369-378.

Reynolds, C.M., Wolf, D.C. and Armbruster, J.A. 1985. Factors related to urea hydrolysis in soils. Soil Sci. Soc. Am. J. 49:104–108.

Rieke, P. E. and Ellis, B. G. 1974. Effects of nitrogen fertilization on nitrate movements under turfgrass. p. 120-130. In: E.C. Roberts (ed.). Proc. 2nd Intl. Turfgrass Res. Conf., Blacksburg, Va. 17-21 June 1973. ASA, Madison, Wis.

Römheld, V. and Kirkby, E.A. 2010. Research on potassium in agriculture: Needs and prospects. Plant and Soil 335:155–180.

Salman, O. A., Hovakeemian, G. and Khraishi, N. 1989. Polyethylene-coated urea. 2. Urea release as affected by coating material, soil type and temperature. Industrial and Engineering Chemistry Research 28:633-638.

Sartain, J. B., Hall, W. L., Littell, R. C. and Hopwood, E. W. 2004. New tools for the analysis and characterization of slow-release fertilizers. Environmental Impact of Fertilizer on Soil and Water 872:180-195.

Shaviv, A., 2000. Advances in controlled release of fertilizers. Adv. Agron. 71:1–49.

Simonne, E. H. and Hutchinson, C. M. 2005. Controlled-release fertilizers for vegetable production in the era of best management practices: Teaching new tricks to an old dog. HortTechnology 15:36-46.

Sinsabaugh, R.S. 1994. Enzymic analysis of microbial pattern and process. Biol. Fert. Soils 17:69–74.

Snyder, G.H., Augustin, B.J. and Davidson, J.M. 1984. Moisture sensor-controlled irrigation for reducing N leaching in bermudagrass turf. Agron. J. 76:964.

Soares, J.R., Cantarella, H. and Menegale, M.L. de C. 2012. Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. Soil Biol. Biochem. 52:82–89.

Spangenberg, B. G., Fermanian, T. W. and Wehner, D. J. 1986. Evaluation of liquid-applied nitrogen fertilizers on Kentucky bluegrass turf. Agron. J. 78:1002-1006.

Starr, J.L. and DeRoo, H.C. 1981. The fate of nitrogen-fertilizer applied to turfgrass. Crop Sci. 21:531–536.

Stephens, H. W. 1997. The Texas City Disaster, 1947. University of Texas Press.

Stevenson, F. J. and Cole, M. A. 1999. Cycles of soils: carbon, nitrogen, phosphorus, sulfur, micronutrients. John Wiley and Sons.

Subbarao, G. V. Ishikawa, T., Ito, O., Nakahara, K., Wang, H. Y., and Berry, W. L. 2006. A bioluminescence assay to detect nitrification inhibitors released from plant roots: A case study with *Brachiaria humidicola*. Plant and Soil 288:101–112.

Telenko, D. E., Shaddox, T. W., Unruh, J. B., and Trenholm, L. E. 2015. Nitrate leaching, turf quality, and growth rate of ‘Floratam’ St. Augustinegrass and common centipedegrass. Crop Sci. 55:1320-1328.

Thiemann, M., Scheibler, E. and Wiegand, K.W. 2012. Nitric acid, nitrous acid, and nitrogen oxides. Ullmann’s Encyclopedia of Industrial Chemistry 24:177-223.

Titko, S., Street, J.R. and Logan, T.J. 1987. Volatilization of ammonia from granular and dissolved urea applied to turf grass. Agron. J. 79:535.

Torello, W. A., Wehner, D.J. and Turgeon, A. J. 1983. Ammonia volatilization from fertilized turfgrass stands. Agron. J. 75:454.

Trenholm, L. E., Duncan, R. R. and Carrow, R. N. 1999. Wear tolerance, shoot performance, and spectral reflectance of seashore paspalum and bermudagrass. Crop Sci. 39:1147-1152.

Trenholm, L.E., Unruh, J.B. and Sartain, J.B. 2012. Nitrate leaching and turf quality in established “Floratam” St. Augustinegrass and “Empire” Zoysiagrass. J. Environ. Qual. 41:793-799.

Trenkel, M. E. 2010. Slow-and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. IFA, International fertilizer industry association. http://www.fertilizer.org/imis20/images/Library_Downloads/2010_Trenkel_slow%20release%20book.pdf

Tyson, J. 1936. Snow mold injury to bentgrasses. Quart. Bull. Michigan Agr. Exp. Sta. 19:87-92.

Urbansky, E.T., Brown, S.K., Magnuson, M.L. and Kelty, C.A. 2001. Perchlorate levels in samples of sodium nitrate fertilizer derived from Chilean caliche. Environ. Poll. 112:299–302.

Vanini, J. T., Henderson, J. J., Sorochan, J. C., and Rogers, J. N. 2007. Evaluating traffic stress by the Brinkman traffic simulator and Cady traffic simulator on a Kentucky bluegrass stand. Crop Sci. 47:782-784.

Volk, G.M. 1959. Volatile loss of ammonia following surface application of urea to turf or bare soils. Agron. J. 51:746-749.

Wang, F.L. and Alva, A.K. 1996. Leaching of nitrogen from slow-release urea sources in sandy soils. Soil Sci. Soc. Am. J. 1458:1454–1458.

Wilkinson, J. F. 1977. Effect of IBDU and UF rate, date, and frequency of application on Merion Kentucky bluegrass. Agron. J. 69:657-661.

Wilson, F. N. 1988. Slow release--true or false?: a case for control. Proceedings of Fertiliser Society, UK. No. 268 34 p.

Wilson, M.L., Rosen, C.J. and Moncrief, J.F. 2009. A comparison of techniques for determining nitrogen release from polymer-coated urea in the field. HortScience 44:492–494.

Wong, J., Chan, C. and Cheung, K. 1998. Nitrogen and phosphorus leaching from fertilizer applied on golf course: Lysimeter study. Water, Air Soil Poll. 107:335–345.

Zahran, H. H. 1999. Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. Microbiology and molecular biology reviews 63:968-989.

Zapp, K. H., Wostbrock, K. H., Schäfer, M., Sato, K., Seiter, H., Zwick, W., Creutziger, R. and Leiter, H. 2000. Ammonium Compounds. Ullmann's Encyclopedia of Industrial Chemistry.

Zhang, M., Nyborg, M., Malhi, S. S. and Solberg, E. D. 2000. Yield and protein content of barley as affected by release rate of coated urea and rate of nitrogen application. Journal of Plant Nutrition 23:401-412.

Table 1. Fertilizers and treatment dates of each experiment. Experiments 1 and 3 were conducted at the Auburn University Turfgrass Unit (TGRU) with artificial traffic, while Experiments 2 and 4 had natural foot traffic.

Exp. No.	**Start date**	**Fertilizers used**	**Coating type**	**N%**	**Manufacturer**
1	22 SEP. 2015, 21 OCT. 2015, 30 OCT. 2015.	DURATION CR® Urea 45 Day 44-0-0 SGN 250 [ƚ]	PCU-1 [ƚ]	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 90 Day 44-0-0 SGN 250	PCU-2	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 120 Day 43-0-0 SGN 250	PCU-3	43	Koch Agronomic Services, LLC
		DURATION CR® Urea 180 Day 43-0-0 SGN 250	PCU-4	43	Koch Agronomic Services, LLC
		XCU® fertilizer 43-0-0 SGN 250 [ǂ]	PCSCU-1 [ǂ]	43	Koch Agronomic Services, LLC
		LESCO® Poly Plus® 39-0-0 [ǂ]	PCSCU-2	39	LESCO. Inc.
2	09 NOV. 2015, 30 NOV. 2015, 19 APR. 2016.	DURATION CR® Urea 45 Day 44-0-0 SGN 250	PCU-1	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 90 Day 44-0-0 SGN 250	PCU-2	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 120 Day 43-0-0 SGN 250	PCU-3	43	Koch Agronomic Services, LLC
		DURATION CR® Urea 180 Day 43-0-0 SGN 250	PCU-4	43	Koch Agronomic Services, LLC
		XCU® fertilizer 43-0-0 SGN 250	PCSCU-1	43	Koch Agronomic Services, LLC
		LESCO® Poly Plus® 39-0-0	PCSCU-2	39	LESCO. Inc.
3	07 JUN. 2016.	DURATION CR® Urea 45 Day 44-0-0 SGN 250	PCU-1	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 90 Day 44-0-0 SGN 250	PCU-2	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 120 Day 43-0-0 SGN 250	PCU-3	43	Koch Agronomic Services, LLC
		DURATION CR® Urea 180 Day 43-0-0 SGN 250	PCU-4	43	Koch Agronomic Services, LLC
4	24 JUL. 2016.	DURATION CR® Urea 45 Day 44-0-0 SGN 250	PCU-1	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 90 Day 44-0-0 SGN 250	PCU-2	44	Koch Agronomic Services, LLC
		DURATION CR® Urea 120 Day 43-0-0 SGN 250	PCU-3	43	Koch Agronomic Services, LLC
		DURATION CR® Urea 180 Day 43-0-0 SGN 250	PCU-4	43	Koch Agronomic Services, LLC

[ƚ] polymer-coated urea

[ǂ] polymer-coated, sulfur-coated urea.

Table 2. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 1, Auburn, AL.

	Pr > F		
sampling date	day 1	day 3	day 7
Run	0.6365	0.0237	0.3221
Traffic (T)	<.0001	0.0003	0.0113
Nsource (N)	<.0001	<.0001	<.0001
N x T	0.0023	0.1721	<.0001

Table 3. Percent N release as affected by traffic and N source, artificial traffic applied, Experiment 1, Auburn, AL. Data shown is averaged over three runs of the experiment.

	days after application								
	1			3			7		
	Percent								
Fertilizer	Traffic	None	P-value	Traffic	None	P-value	Traffic	None	P-value
Urea 45 day	7.0 b	2.6 b	0.038	16.0 bc	6.4 b	0.0009	23.3 ab	11.3 a	0.0014
Urea 90 day	12.6 b	6.7 b	0.096	11.3 c	7.5 b	0.17	16.0 b	10.8 b	0.12
Urea 120 day	6.3 b	1.9 b	0.24	7.9 c	2.3 b	0.038	9.6 b	6.6 b	0.069
Urea 180 day	3.2 b	0.3 b	0.97	2.4 c	5.1 b	0.31	5.9 b	7.9 a	0.44
XCU	16.7 b	11.6 b	0.26	26.6 b	18.3 b	0.074	33.0 a	22.1 ab	0.028
Poly plus	56.8 a	38.1 a	0.0046	42.1 a	32.9 a	0.22	16.6 b	26.5 a	0.021

[†] Within each sampling date, under the same treatment (within a column), means followed by the same letter are not significantly different at α= 0.05. This shows differences due to N source.

[‡] P-values show comparisons within that fertilizer, trafficked or not (within a row and sampling day).

Table 4. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 2, Auburn, AL.

	Pr > F
Sampling date	day 7
Run	0.404
Traffic (T)	0.2786
N source (N)	0.0001
N x T	0.0685
Run x N x T	0.4052

Table 5. Percent N release as affected by traffic and N source, real human traffic applied, Experiment 2, Auburn, AL. Data shown is averaged over three runs of the experiment.

Fertilizer	Days after application		
	7		
	% N release		
	Traffic	None	P-values[‡]
Urea 45 day	13.0 b	7.8 c	0.15
Urea 90 day	11.0 bc	7.5 c	0.34
Urea 120 day	6.3 c	4.8 c	0.44
Urea 180 day	5.0 c	4.4 c	0.71
XCU	30.0 a	26.0 b	0.15
Poly Plus	28.0 a	35.0 a	0.11

[‡] Within each column, under the same treatment, means followed by the same letter are not significantly different at α= 0.05. This is the comparison due to N source.

[‡] P-values show comparisons between traffic versus non-traffic, within each fertilizer source.

Table 6. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 3, Auburn, AL.

Source	Pr > F
Replication	0.6763
Traffic (T)	0.0607
N source (N)	0.0001
N x T	0.9653
Rep x N x T	1.0000

Table 7. Comparison of N release as affected by sampling week, N source and traffic, artificial traffic applied.

Nsource	trt	Week 1	Week 3	Week 5	Week 7	Week 9
Urea 45 day	traffic	45.0 d	75.7 bc	72.7 c	84.3 ab	86.8 a
	none	46.6 c	70.2 b	68.4 b	77.3 ab	85.9 a
	p-value	0.76	0.33	0.037	0.19	0.89
Urea 90 day	traffic	12.1 d	43.2 c	39.8 c	55.0 b	65.3 a
	none	11.7 d	28.0 c	40.2 bc	52.3 ab	56.3 a
	p-value	0.92	0.059	0.92	0.53	0.28
Urea 120 day	traffic	7.8 c	20.1 c	38.8 b	51.4 ab	55.6 a
	none	1.2 d	19.5 c	31.4 b	43.0 a	45.6 a
	p-value	0.016	0.93	0.38	0.10	0.32
Urea 180 day	traffic	3.3 d	29.4 bc	23.9 c	40.7 ab	52.0 a
	none	3.8 c	15.9 b	23.4 b	33.6 a	36.1 a
	p-value	0.66	0.16	0.91	0.26	0.12

[ŧ] Within each fertilizer and traffic treatment (row), means followed by the same letter are not significantly different from each other at α= 0.05.

[ǂ] P-values show comparisons between treatments at a given sampling week (traffic versus none), within each fertilizer.

Table 8. Analysis of variance for measured N release from fertilizer prills as affected by traffic, Experiment 4, Auburn, AL.

Source	Pr > F
Replication	0.9789
Traffic (T)	0.8370
N source (N)	0.0001
N x T	0.7581
Rep x N x T	0.9991

Table 9. Comparison of nitrogen release percentage between different sampling dates by real human traffic. Experiment 4, Auburn, AL.

Nsource	trt	Week 1	Week 3	Week 5	Week 7
Urea 45 day	traffic	39.7 c	63.9 b	75.0 a	78.2 a
	none	29.2 c	55.9 b	71.2 a	76.9 a
	P-value	0.033	0.22	0.51	0.71
Urea 90 day	traffic	24.0 d	36.7 c	53.1 b	62.6 a
	none	17.5 b	52.5 a	54.3 a	58.6 a
	P-value	0.13	0.23	0.78	0.38
Urea 120 day	traffic	7.9 c	27.1 b	41.5 ab	53.1 a
	none	3.4 d	27.1 c	41.5 b	53.1 a
	P-value	0.27	1	0.81	0.10
Urea 180 day	traffic	0 d	15.3 c	27.1 b	33.2 a
	none	0 c	20.3 b	37.5 a	37.9 a
	P-value	1	0.10	0.28	0.16

[†] Within each traffic treatment and N source means followed by the same letter are not significantly different at α= 0.05.

[‡] P-values show comparisons between traffic versus non-traffic, within each fertilizer source.

Figure 1. The Cady traffic simulator unit, used to apply artificial traffic in Experiments 1 and 3.

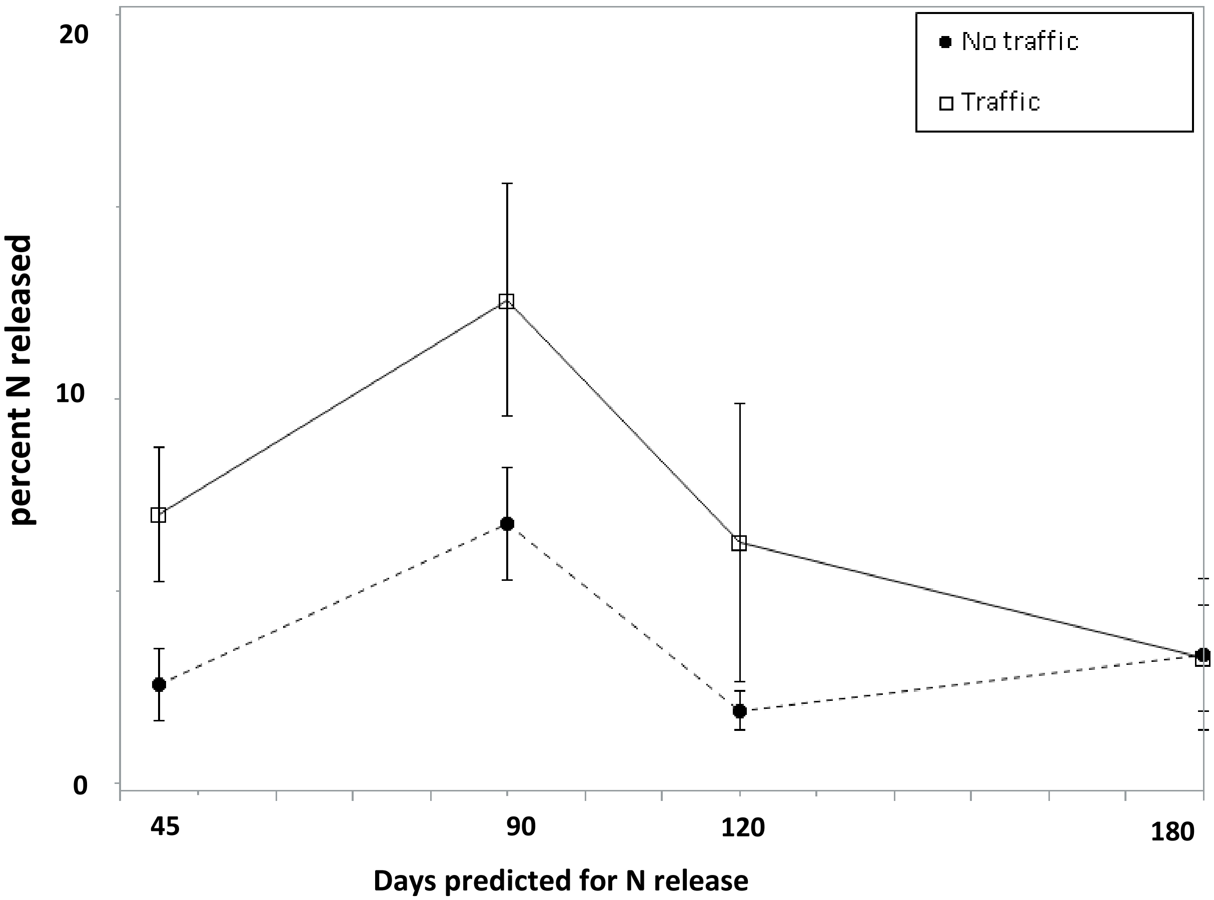

Figure 2. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 1, Experiment 1, Auburn, AL. Error bars are the standard error about the mean.

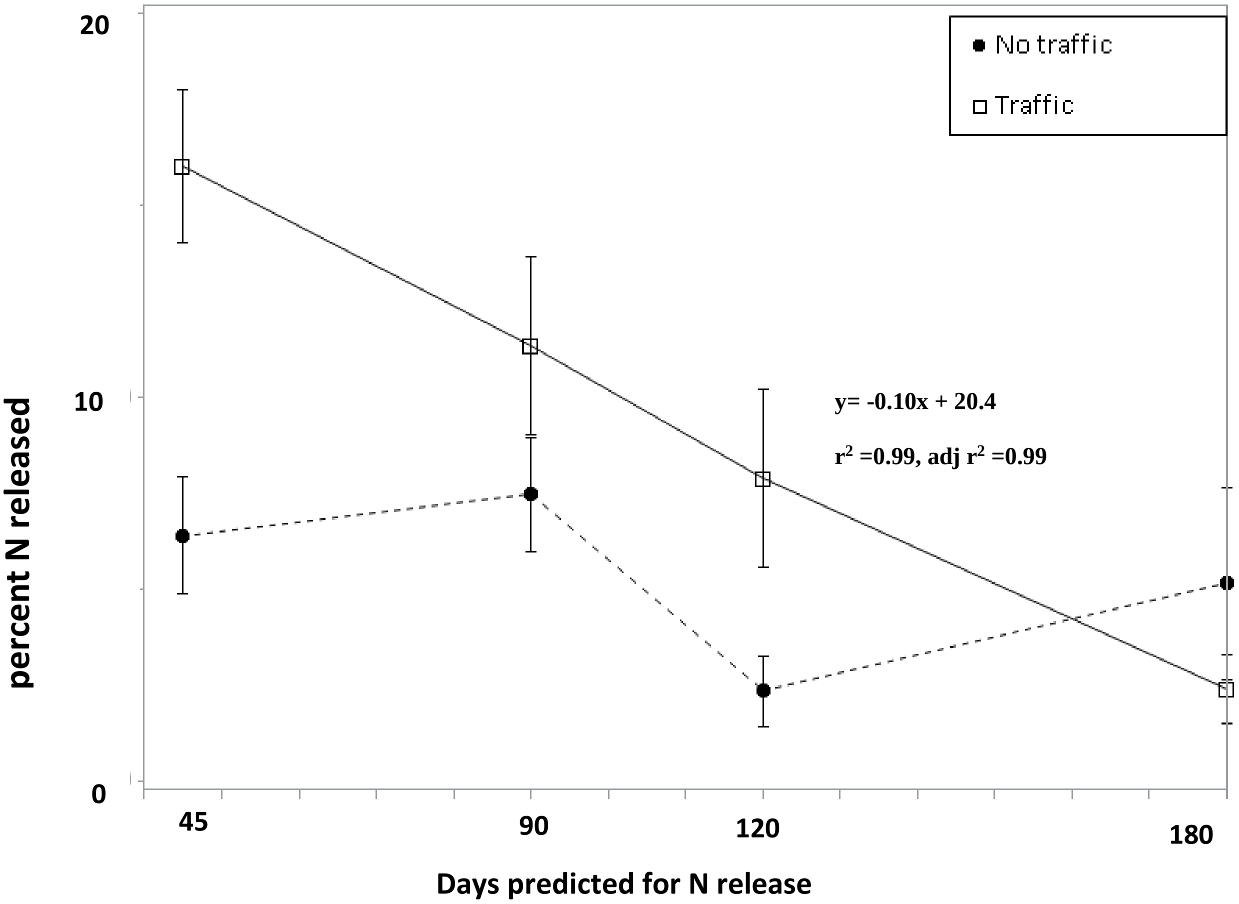

Figure 3. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 3, Experiment 1, Auburn, AL. Error bars are the standard error about the mean. If the regression was significant, that equation is shown.

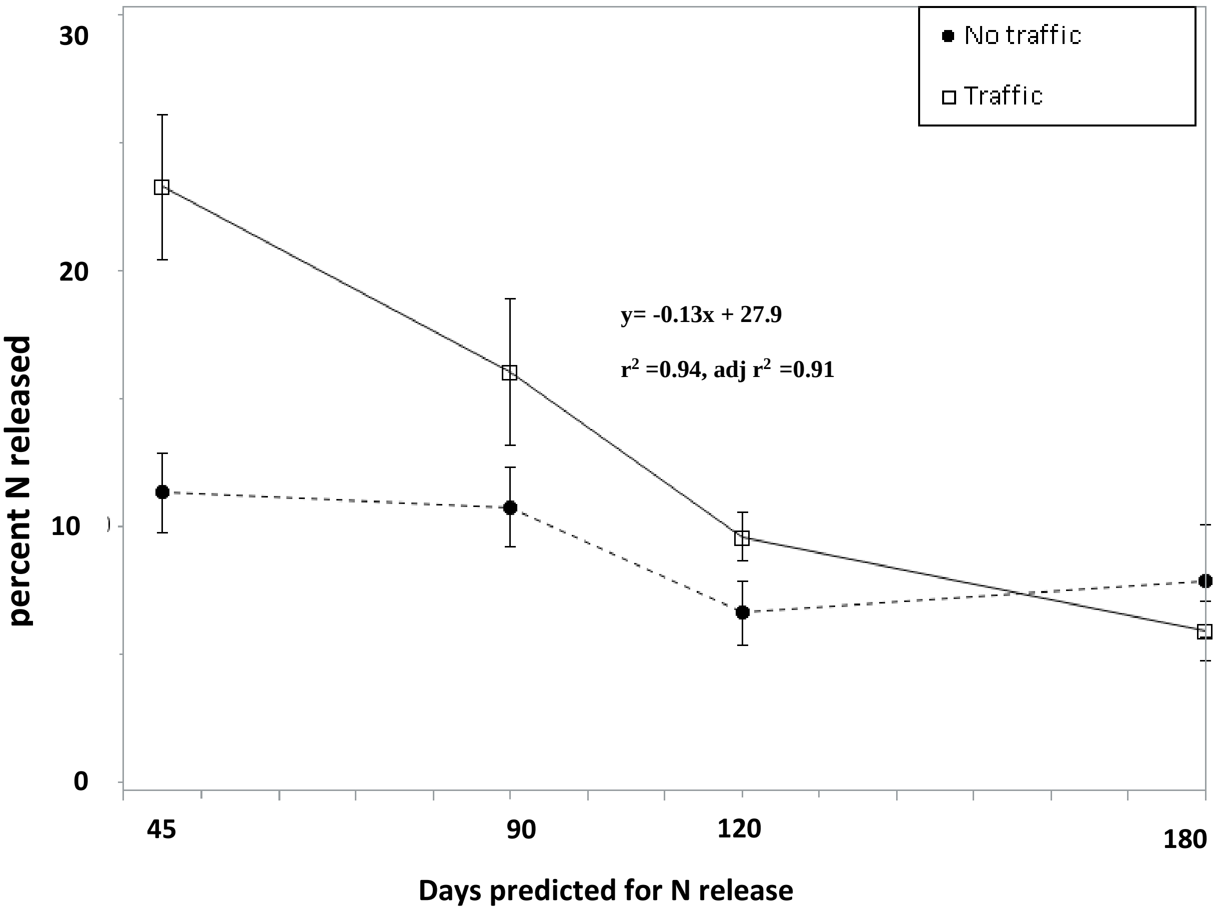

Figure 4. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 7, Experiment 1, Auburn, AL. Error bars are the standard error about the mean. If the regression was significant, that equation is shown.

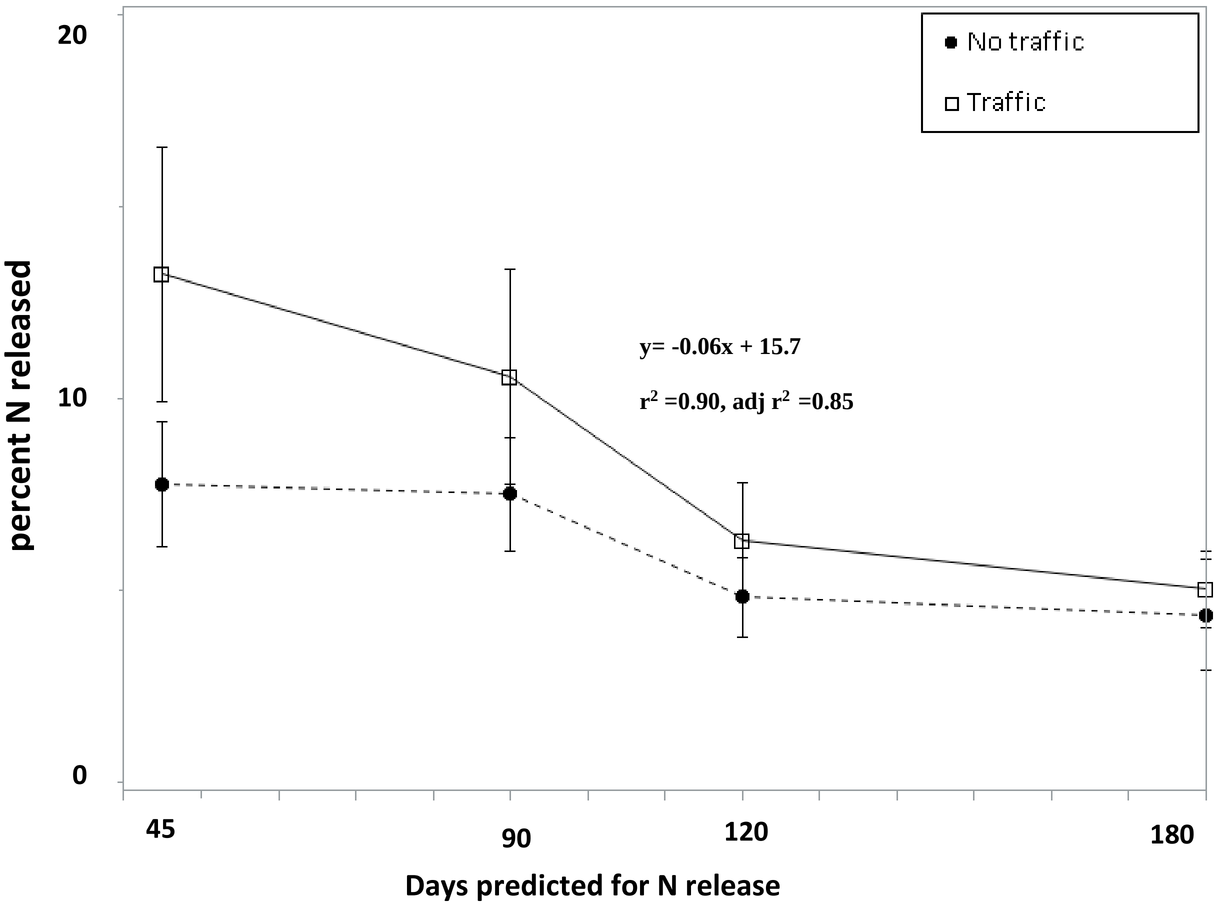

Figure 5. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Day 7, Experiment 2, Auburn, AL. Error bars are the standard error about the mean. If the regression was significant, that equation is shown.

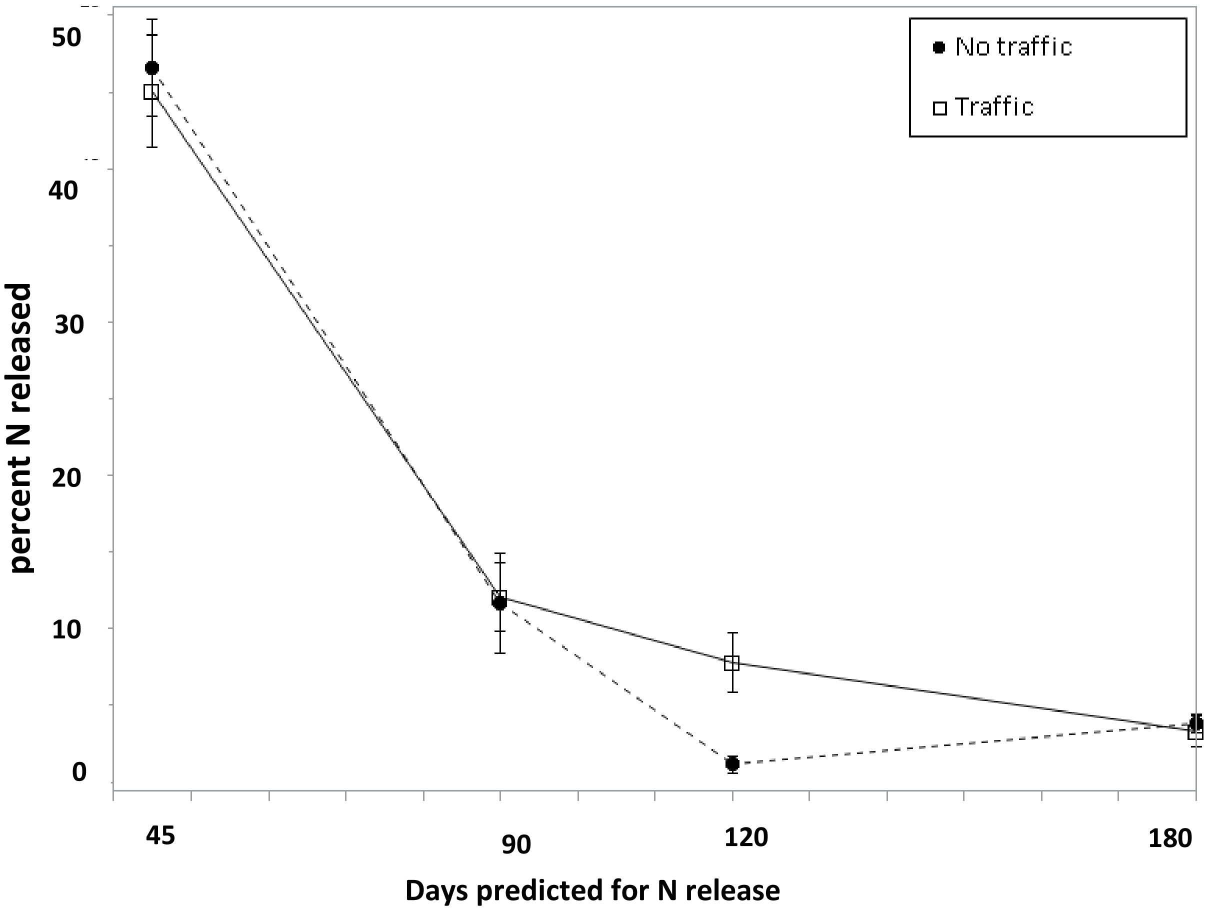

Figure 6. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 1, Experiment 3, Auburn, AL. Error bars are the standard error about the mean.

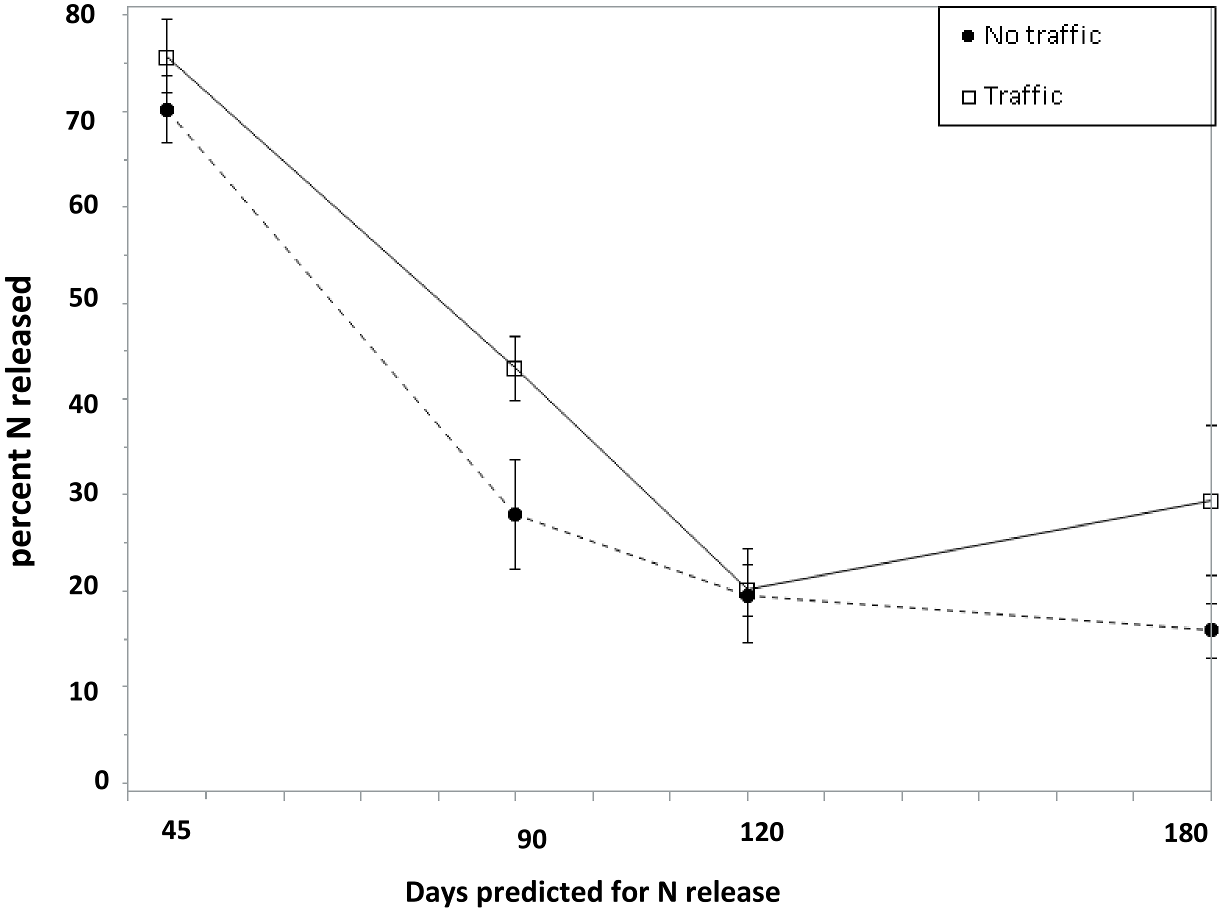

Figure 7. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 3, Experiment 3, Auburn, AL. Error bars are the standard error about the mean.

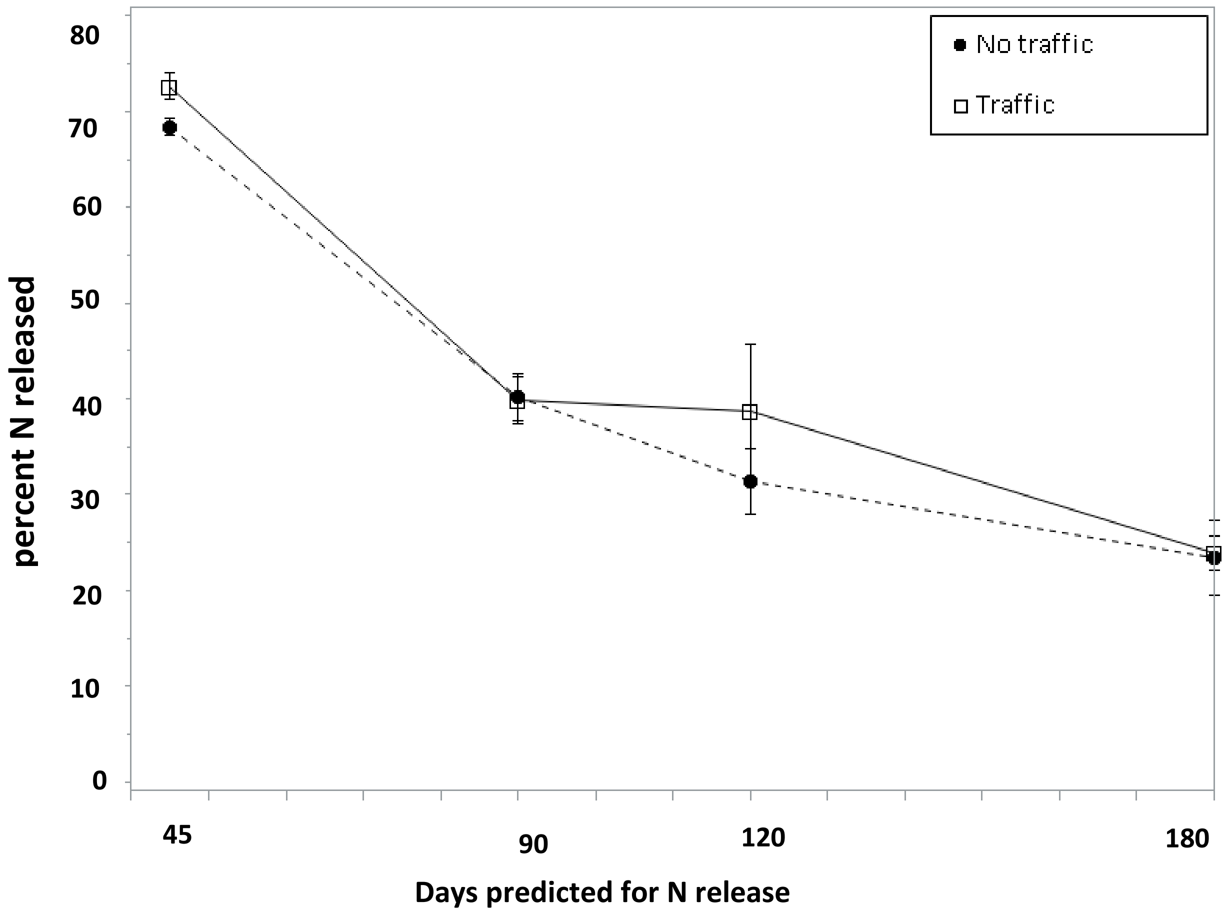

Figure 8. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 5, Experiment 3, Auburn, AL. Error bars are the standard error about the mean.

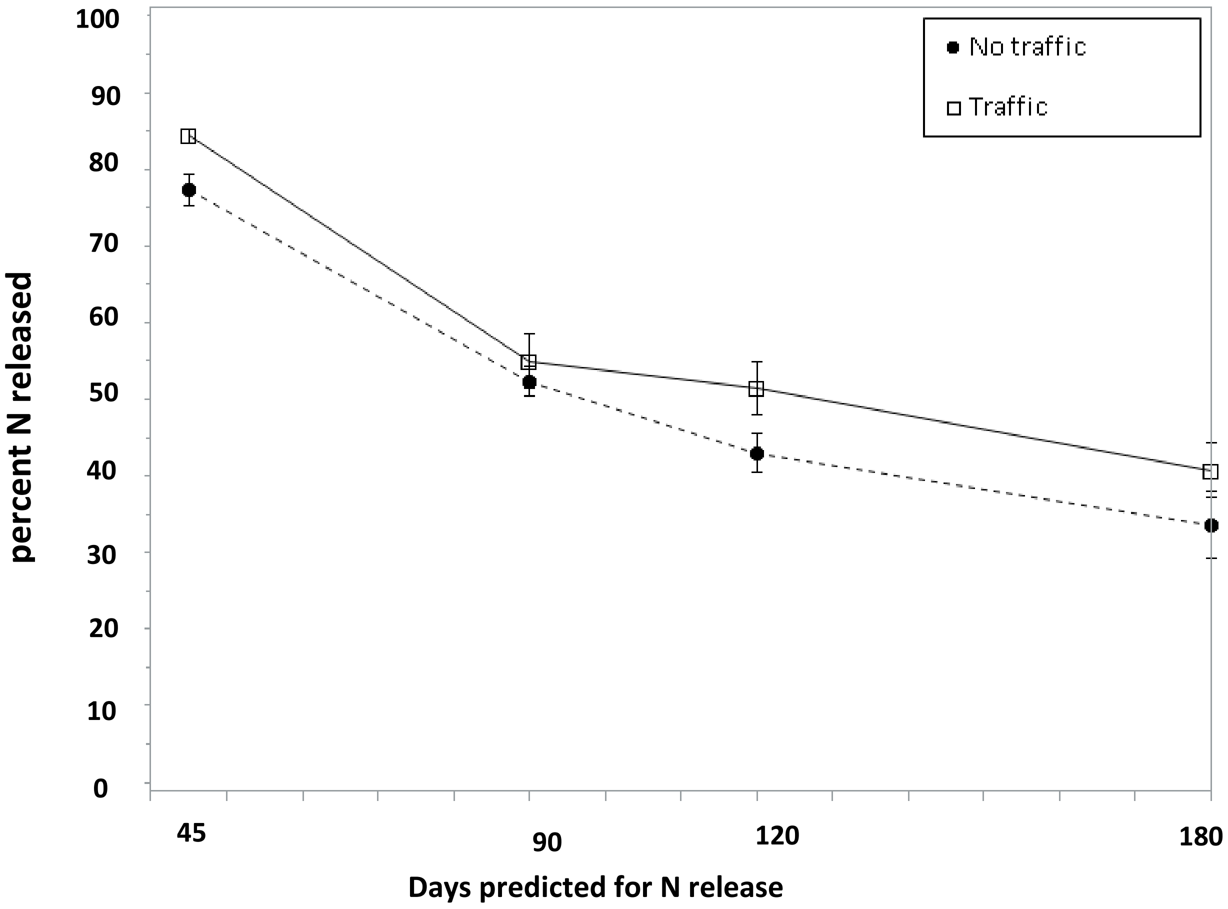

Figure 9. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 7, Experiment 3, Auburn, AL. Error bars are the standard error about the mean.

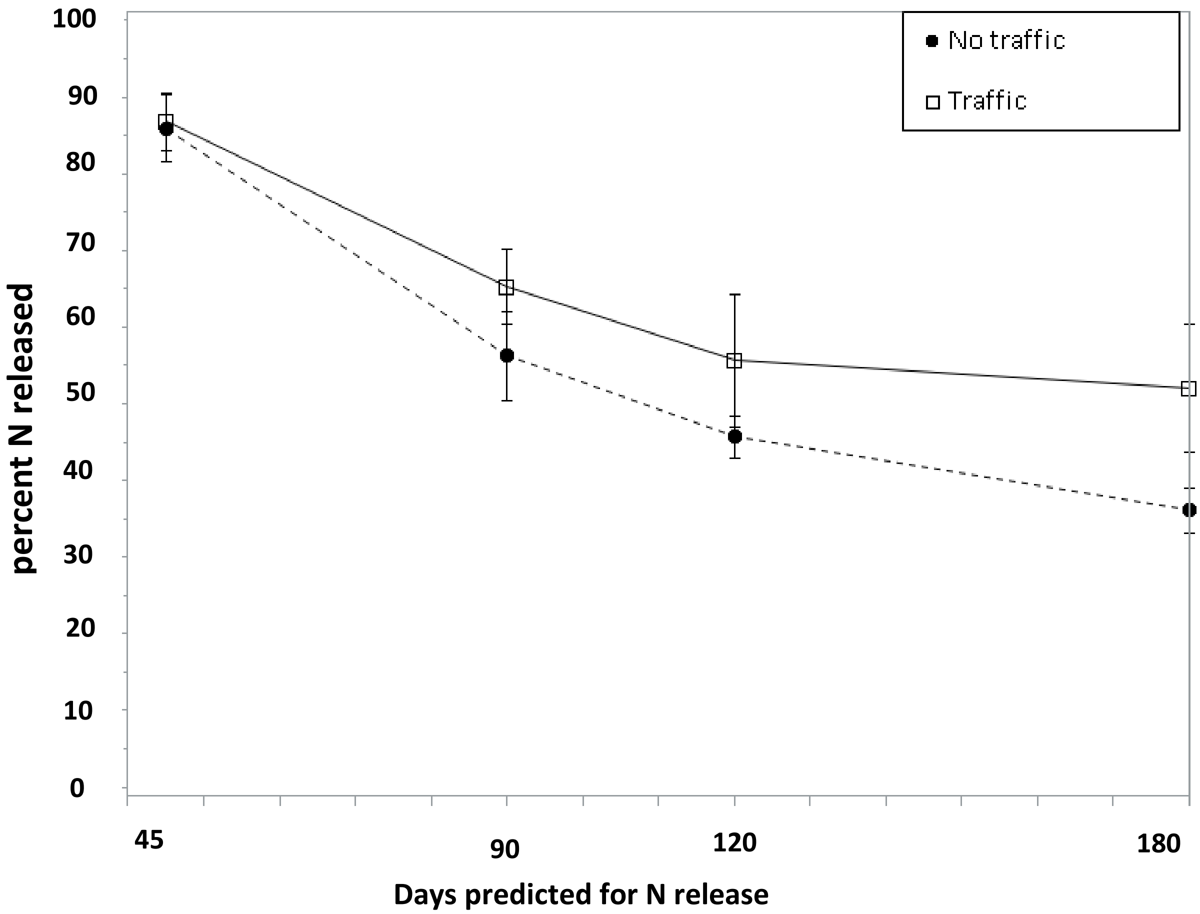

Figure 10. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 9, Experiment 3, Auburn, AL. Error bars are the standard error about the mean.

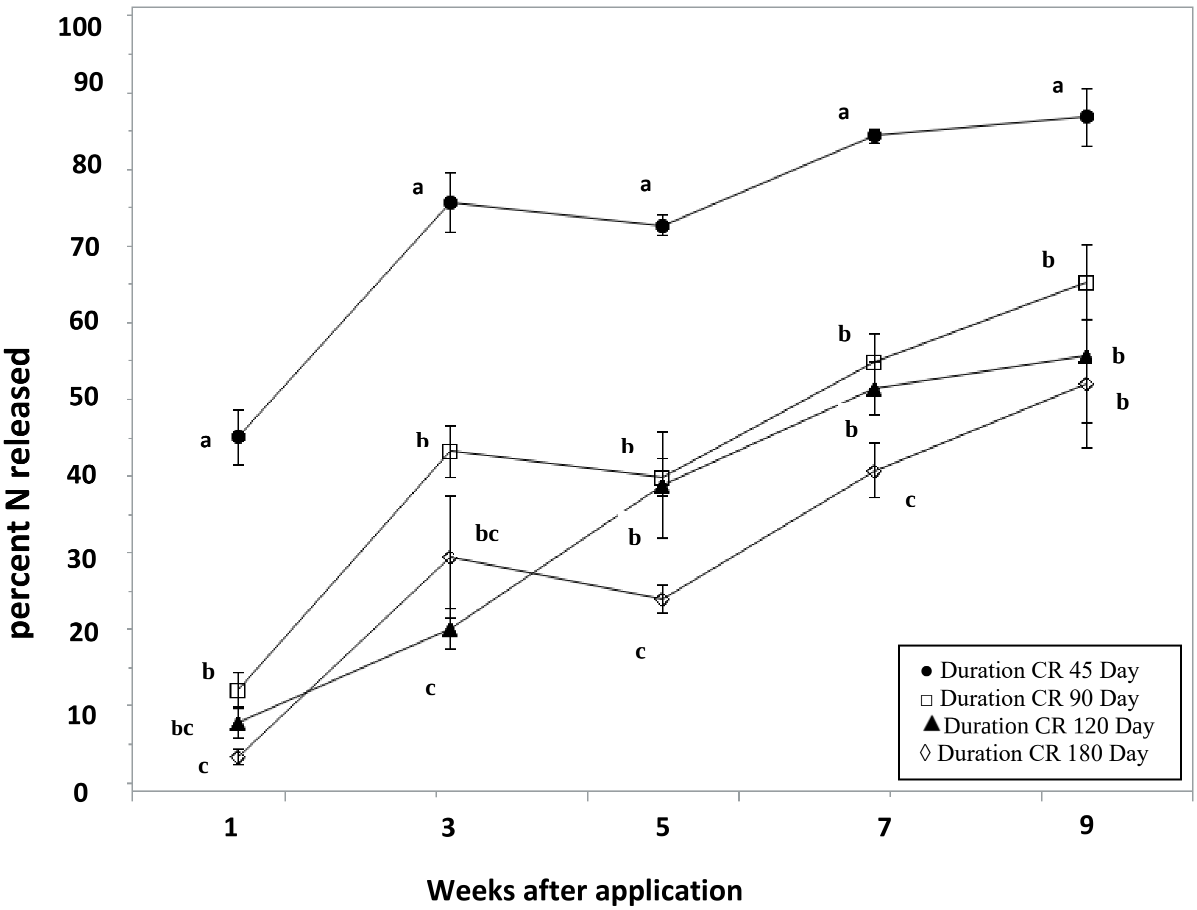

Figure 11. N release by sampling date as affected by coating thickness, trafficked (artificial) plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 3, Auburn, AL.

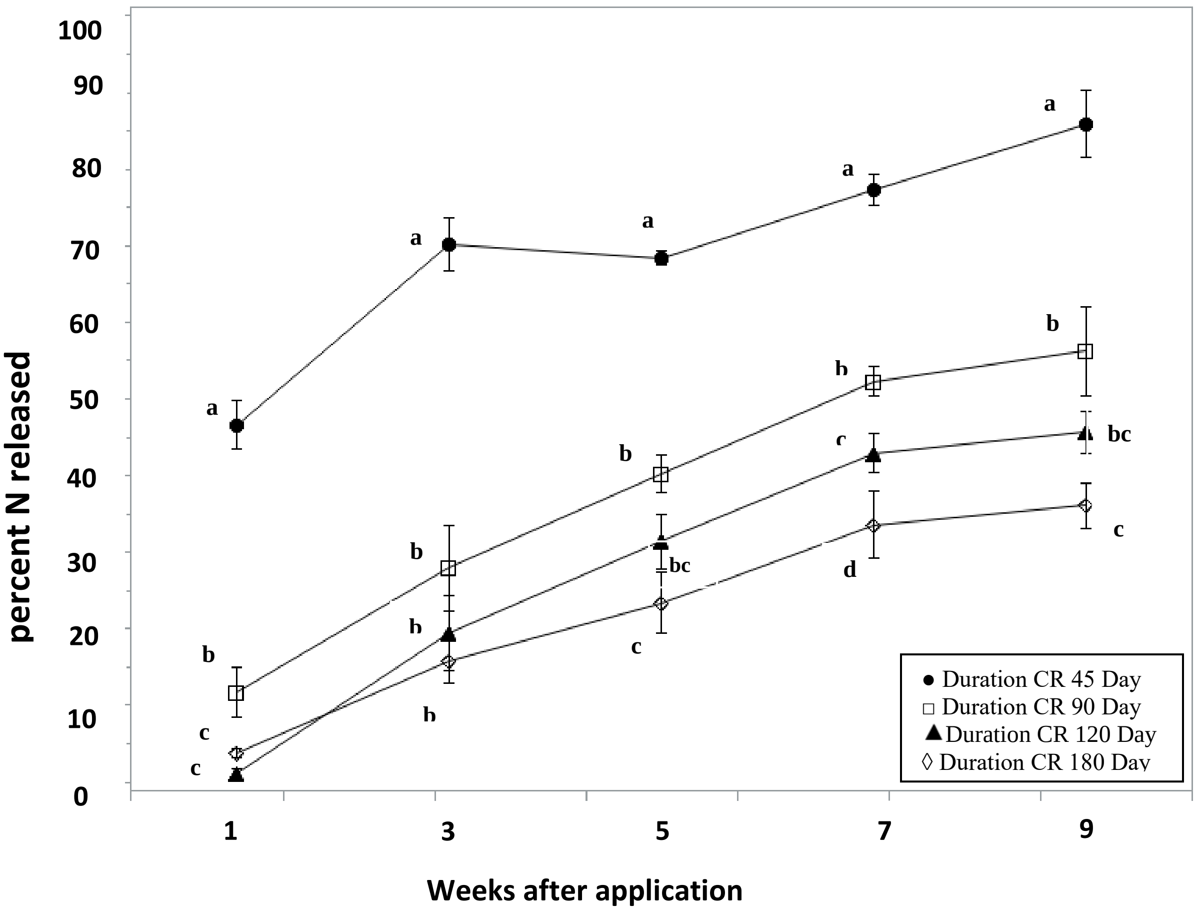

Figure 12. N release by sampling date as affected by coating thickness, non-trafficked plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 3, Auburn, AL.

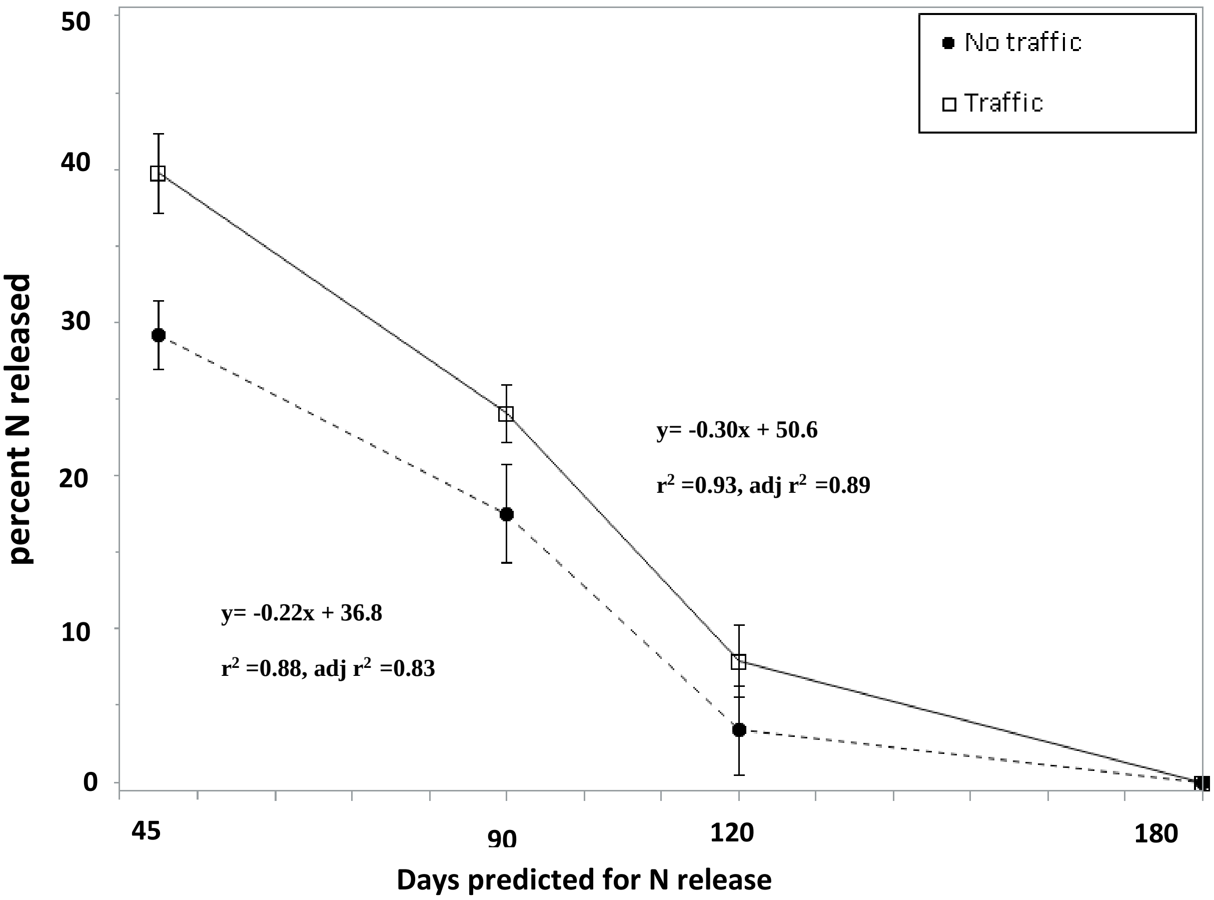

Figure 13. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 1, Experiment 4, Auburn, AL. Error bars are the standard error about the mean. If the regression was significant, that equation is shown.

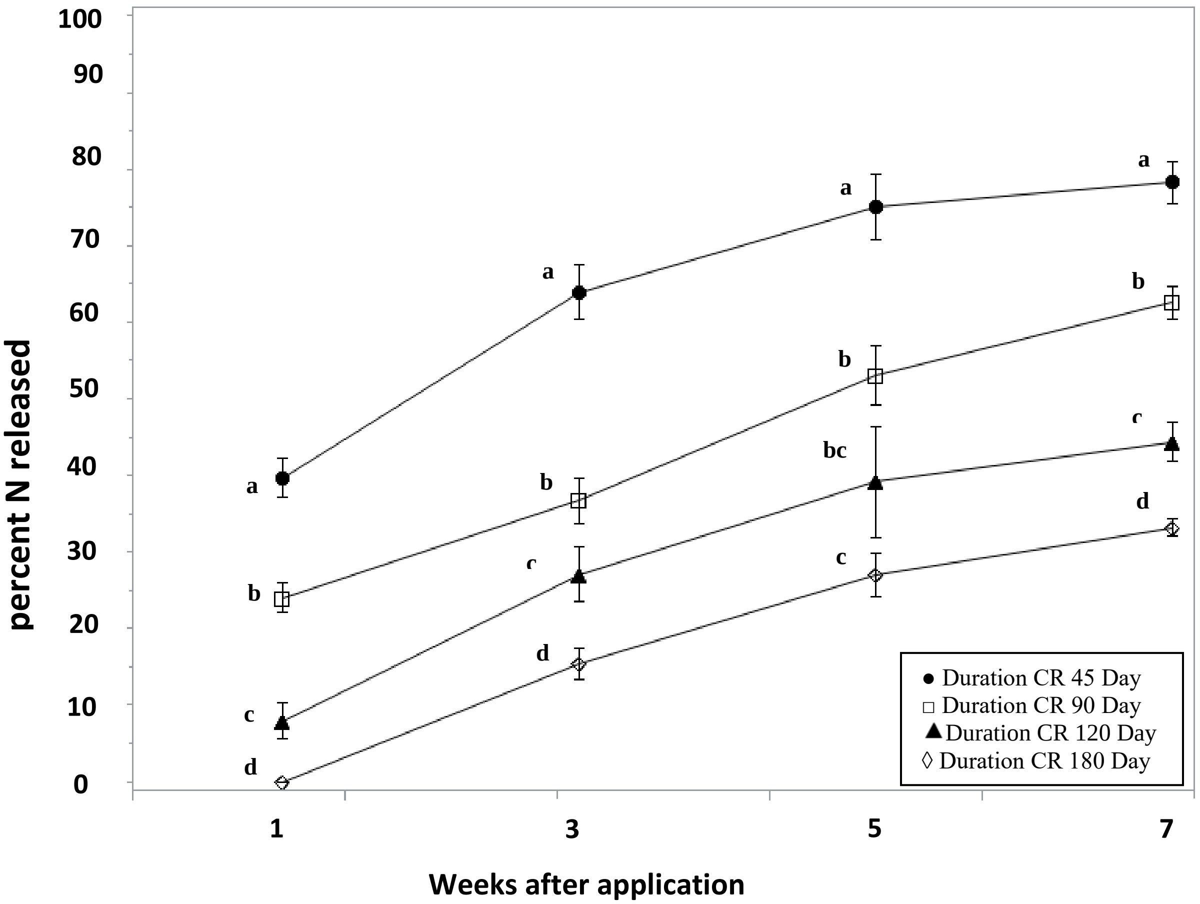

Figure 14. N release by sampling date as affected by coating thickness, trafficked (real human) plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 4, Auburn, AL.

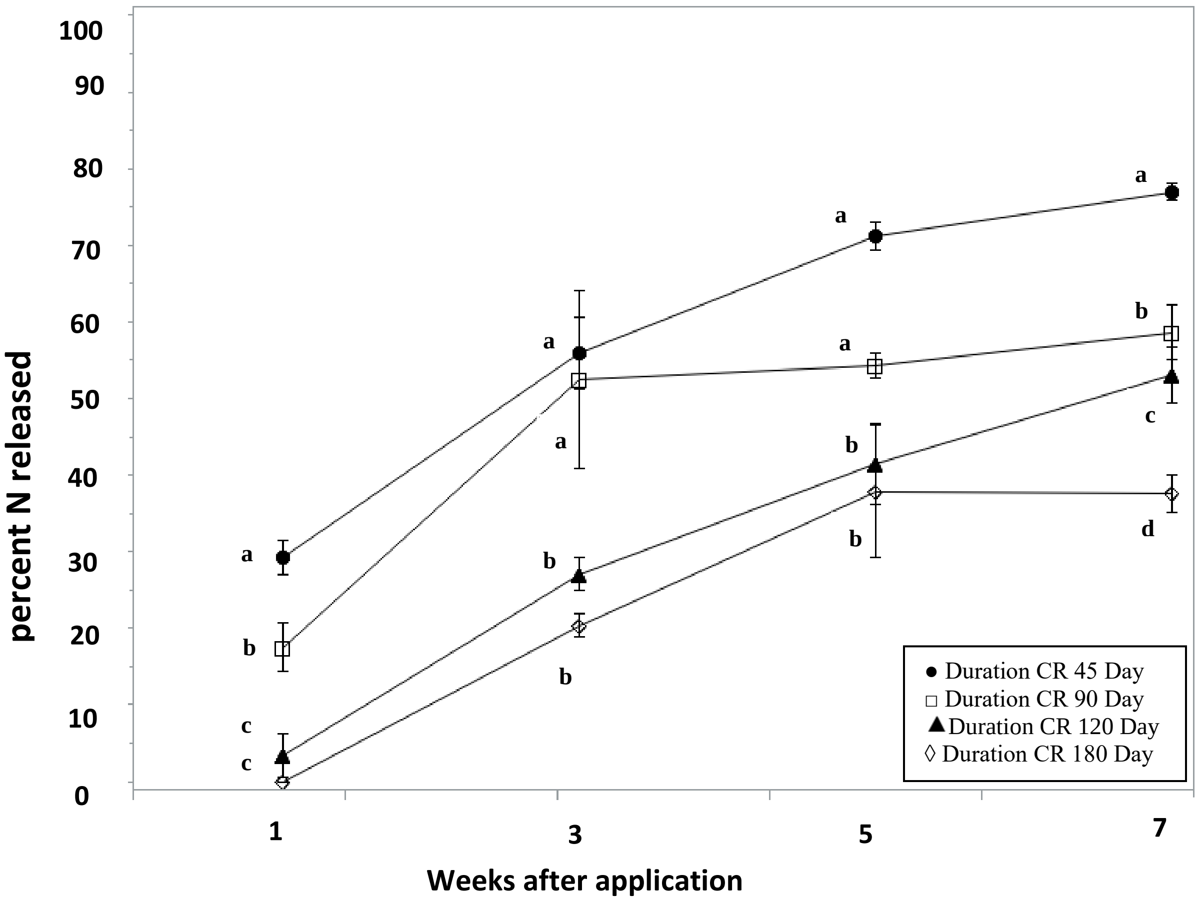

Figure 15. N release by sampling date as affected by coating thickness, non-trafficked plots. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Experiment 4, Auburn, AL.

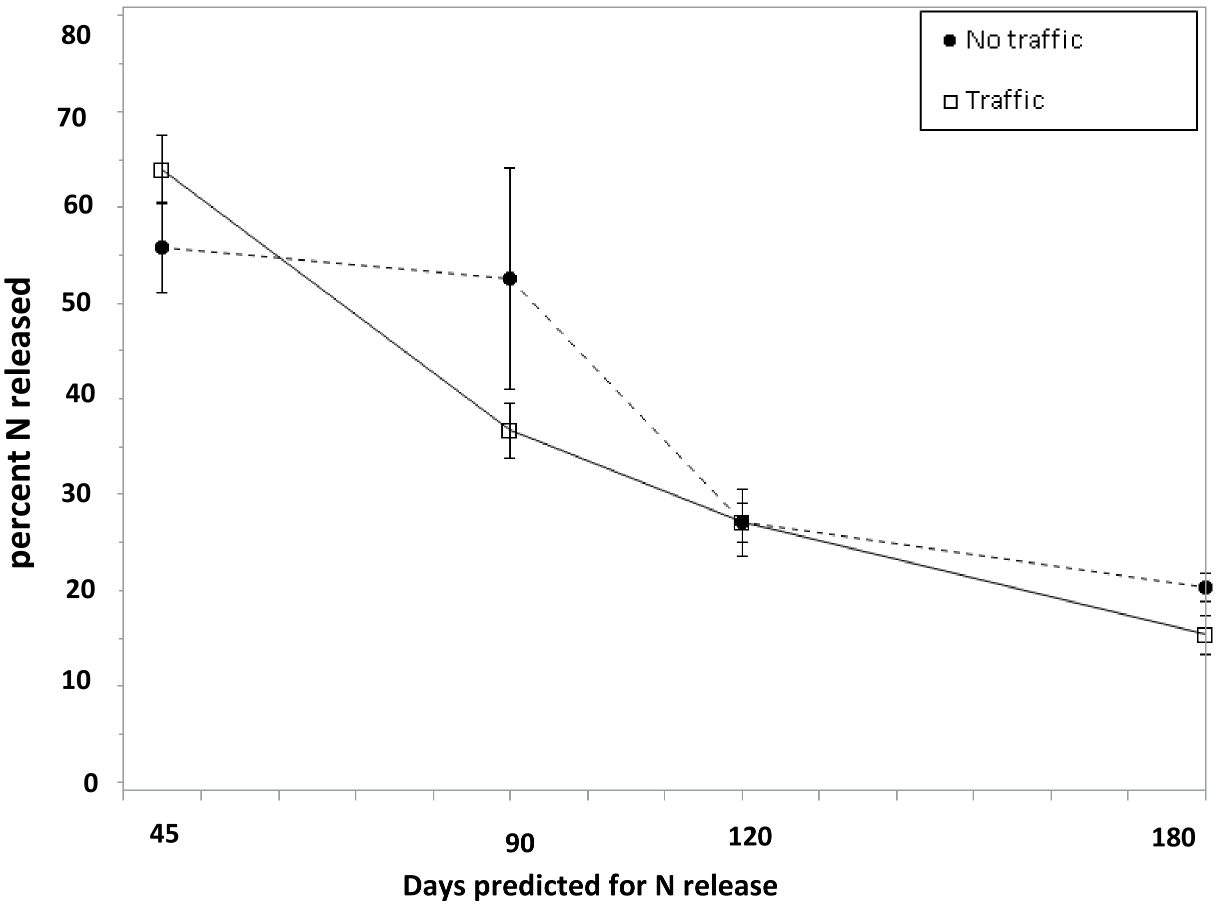

Figure 16. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 3, Experiment 4, Auburn, AL. Error bars are the standard error about the mean.

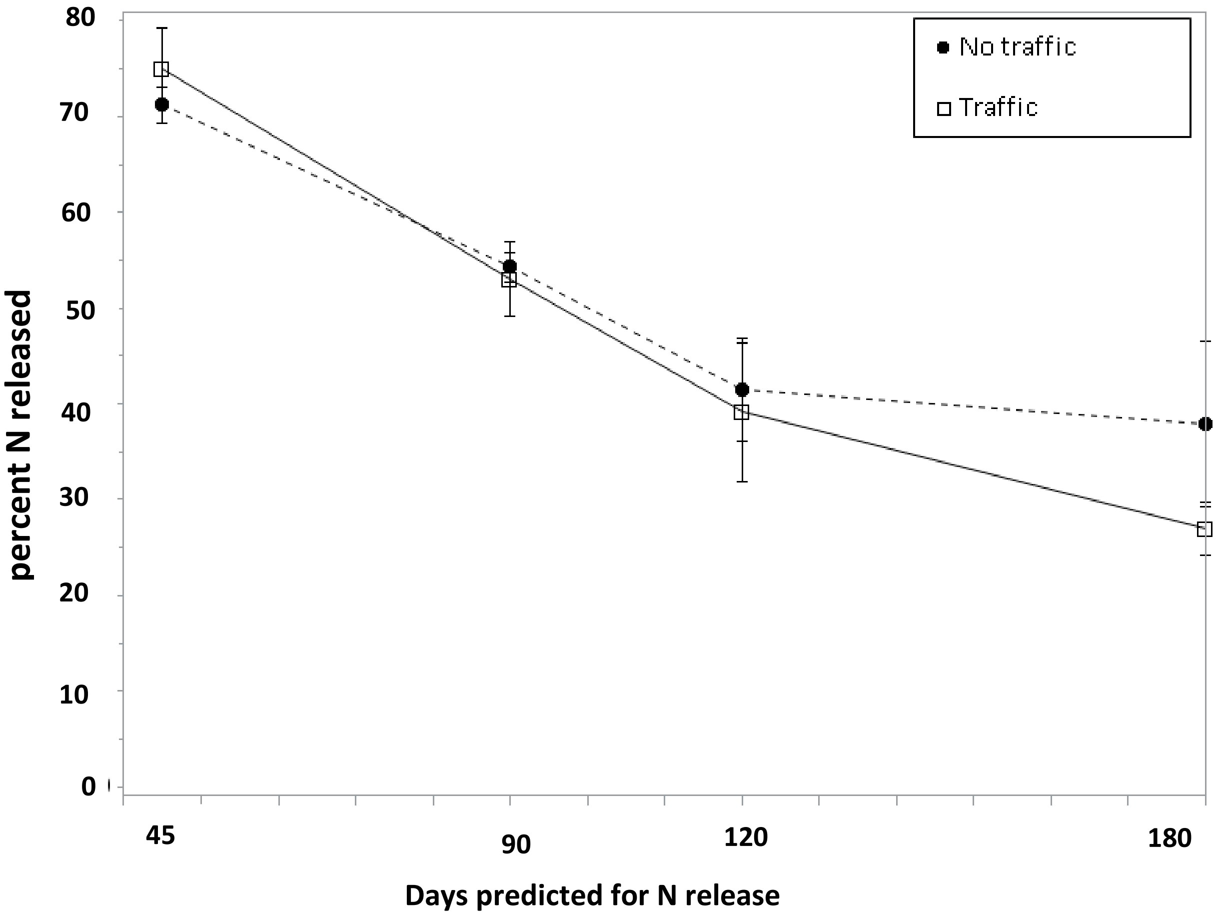

Figure 17. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 5, Experiment 4, Auburn, AL. Error bars are the standard error about the mean.

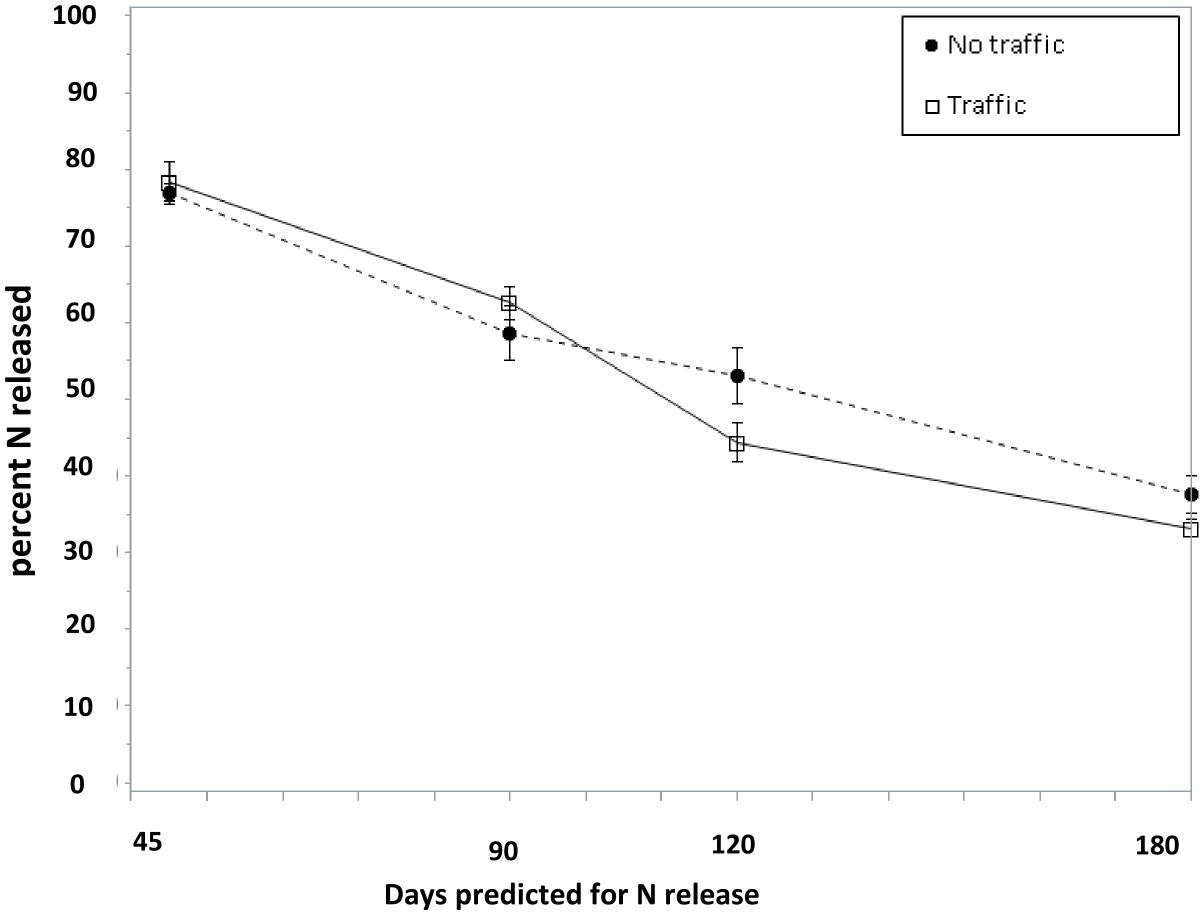

Figure 18. N release of fertilizer sources as affected by coating thickness and traffic. N sources used are the same material and coating type (Duration CR urea), varying only in thickness (days to N release), Week 7, Experiment 4, Auburn, AL. Error bars are the standard error about the mean.