Fertilizer Filtration in Conventional Groundcovers

Ferngren, Jennifer; Cabrales, Angelica; Clark, Spencer; Maynard, Mikael; Otto, Dylan

Introduction

Expansive green lawns are a cultural norm in the US, even a requirement of many communities across the country. In fact, lawn cover in the US surpasses the land coverage of many food crops (Bormann 1993). In Florida, a green lawn can be maintained for most of the year, so picking an efficient ground cover is especially important. A sustainable ground cover should have the ability to filter out chemicals and fertilizers that are regularly applied to lawns. This is important since these chemicals are detrimental to groundwater resources. For the purposes of this study we will be looking at three different ground covers- St. Augustinegrass, Bahiagrass, and Zoysiagrass and their ability to filter fertilizer and ultimately keep it out of the aquifer.

"St. Augustinegrass is the predominant vegetation used in Florida residential landscapes" (Cisar 2001). It provides a nice, bright green lawn and is fairly shade tolerant. On the down side, it requires a substantial amount of irrigation and is not drought tolerant (Trenholm 2013). Bahiagrass is another popular choice for lawns in Florida as it requires less watering and fertilizer; however, it is not as popular as St. Augustinegrass due to the formation of long seed stalks that many find unsightly and its shade intolerance (Trenholm 2013). "Zoysiagrass is a popular warm season perennial turfgrass that tolerates stress and unfavorable conditions such as low light, salinity, drought, and cold temperatures" (Stiglbauer 2009). Though all three of these ground cover species have different requirements, they all require fertilization.

Introduction to Fertilizers

The main chemical found in fertilizers is nitrogen. When found in the form of nitrate (NO_3^-), nitrogen is highly reactive and is prone to leaching and runoff (Raciti 2011). “Nitrogen in its various forms has become both an essential agricultural nutrient and a major waste product of society during the past 60 years” (Puckett 2011). “In the two decades following World War II, fertilizer production had spiraled upward by 17 million tons, and nonfarm consumption had become an increasingly large part of the market” (Whitney, 2010). As stated by Robertson and Vitousek, “global nitrogen fertilizer application has increased approximately 10 fold between 1950 and 2008” (2009). This phenomenal shift in lawn care maintenance coincided hand in hand with the rise of the green revolution. The green revolution had a significant impact on global agricultural production, shifting it from a localized cultural practice to a global industry. While the production and use of fertilizers has allowed society to grow more crops and greener lawns than the land could naturally support, the problem is that the excess nitrogen is moving

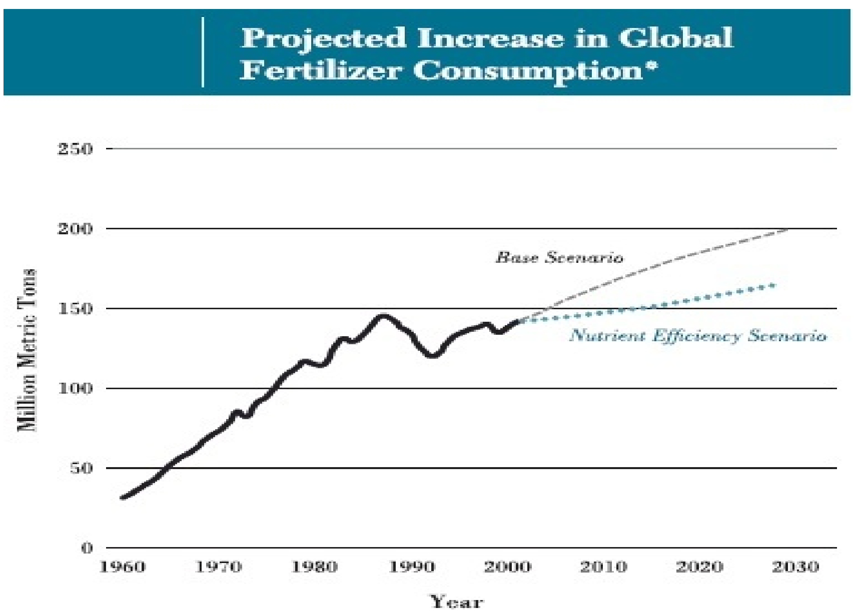


Figure 1 (http://www.wri.org/project/eutrophication/about/drivers) into other natural systems. Figure 1 demonstrates the increasing use of fertilizers. “In intensive agricultural production systems, as much as 50% of the N applied to the field is not used by the crop plant (Cameron et al, 2013). While this paper does not discuss nitrogen pollution due to agricultural fertilizer use, it stands to reason that much of the N being applied to lawns is not being used by the plant.

Introduction to Aquifers

“Globally, groundwater comprises about 99% of available fresh water. As climate change decreases the reliability of surface water systems, populations will turn more to groundwater as a fresh water source. However, groundwater is highly vulnerable to contamination” (Puckett 2011). In Florida, the majority of our water comes from an extensive network of aquifers; the Floridan aquifer system, which is one of the most productive in the US (Van Beynen 2011) “covering an area of 100,000 square miles” (Miller 1990). The Floridan is highly vulnerable to chemical pollution due to the surficial aquifer system which can be seen in Figure 2 that sits close to the surface and is not confined by clay or limestone (FDEP 2007). Figure 3 shows a map of the surficial aquifer system in the southeastern US. When fertilizer is

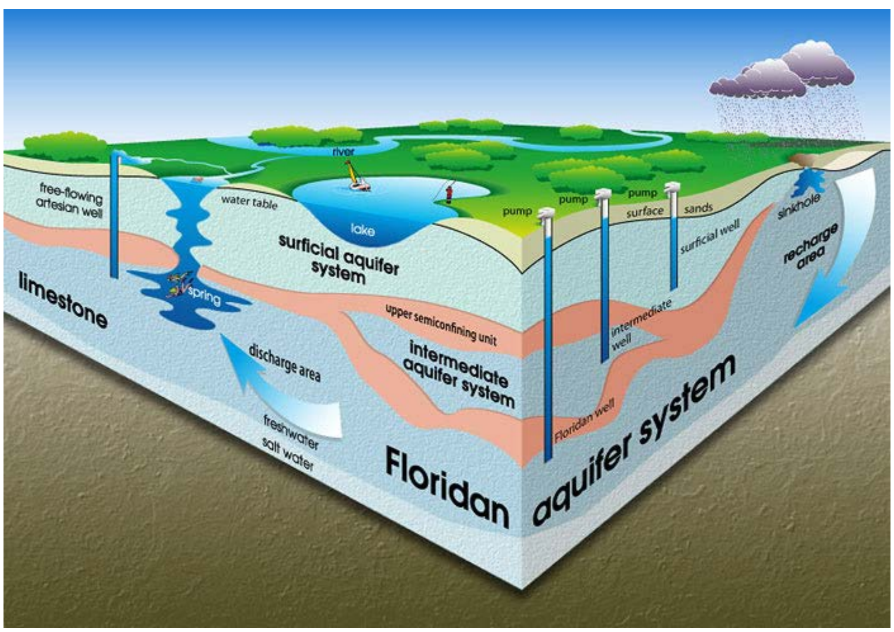
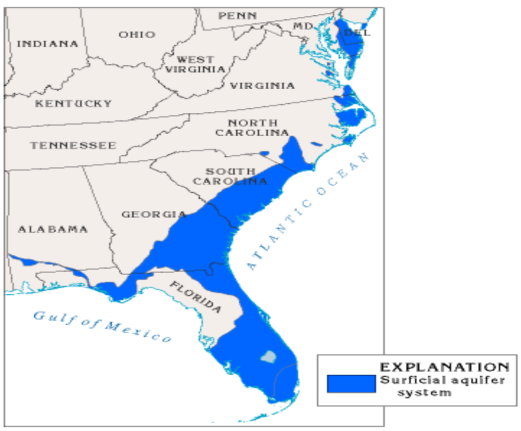


Figure 2. http://hendryutilities.com/docs/boxes/Florida_aquifers_L.jpg

applied to lawns, the plants will use much of it, but the excess is subject to runoff, leaching, and other environmental factors. “Owing to the mobility of nitrate (NO3-), groundwater is vulnerable to contamination from leaching; especially shallow unconfined aquifers” (Puckett 2011). A paper by Farber about linking ecology and economics discusses the trade-offs and values of ecosystem services (2006). We as a community have to place a value on pristine drinking water from the aquifer and consider the replacement cost of that water supply if it is contaminated.



The Surficial aquifer system extends throughout large areas in the Coastal Plain of Florida, Georgia and South Carolina. The Surficial aquifer is the uppermost aquifer in the Northern Atlantic Coastal Plains aquifer system. The surficial aquifer extends over large parts of the Delmarva Penninsula and the eastern coastal plain of North Carolina.

Figure 3 (http://water.usgs.gov/ogw/aquiferbasics/ext_surficiala.html)

Broader Implications

“Groundwater in many urban and peri-urban areas has been significantly affected by pollutants, particularly nitrate” (McDonald 2011). Since, as previously stated, drinking water in Florida comes from groundwater; the fact that it may be contaminated is a frightening prospect. As the population grows and urbanization continues to spread this trend is only going to increase. While there are immediate concerns of contamination there are also future implications. “While high nitrate levels can be a concern on their own, because of long groundwater residence times, steadily declining water quality may result as the fraction of water that predates industrial agriculture decreases with time. The net result is we are creating a N pollution legacy that may affect future generations for decades to come.” (Puckett 2011).

A paper by Callicott discusses the concept of ecological sustainability and describes it as the maintaining at the same place and the same time two interacting things (1997). For the purposes of this study those two things are a bright green lawn and a clean drinking water supply. These are two things that may not be able to continue to exist simultaneously unless preventative and sustainable actions are taken.

“With the urbanization of Florida and the concomitant increase in fertilizer use by home owners, there is growing concern about the impact of nutrient losses from conventional turf grass landscapes as a result of surface water runoff and subsurface leaching” (Erickson 1999). Water that is contaminated with nitrate is not drinkable and could be a health risk at high enough concentrations (Andrews 2013). Studies have linked exposure to NO3 at concentrations lower than the EPA and WHO standards to several cancers and negative birth outcomes (Puckett 2011).

In addition to the negative effects of fertilizer contamination on humans, there are many negative effects on ecosystems.

> “Much of the land cover in newly subdivided suburban lots may, in fact, consist solely of turf grass and as suburbs begin to displace other land covers in the fringe belts surrounding US cities, there is a parallel growth in the coverage of lawns. These bring with them inputs of insecticides, herbicides, and fertilizer. This means changes in soil profile, storm water runoff, water consumption, micro-fauna diversity, energy use, air quality, and opportunities and constraints for terrestrial wildlife and nesting birds” (Robbins 2003).

It is very important to understand how these systems work and interact with each other. While simply applying fertilizer to one’s lawn to keep it green may seem innocent, there are larger implications. As Erickson states in his paper, “fertilizer practices that minimize N runoff and leaching are advantageous to both human safety and the environment” (1999).

With these definite problems in mind, we propose to find the best ground cover for UCF that limits the amount of fertilizer leaching into the groundwater. A previous study by Cisar found that very little N (<2%) leached from St. Augustinegrass (2001). Also, using the knowledge that St. Augustinegrass requires the most fertilizer we hypothesize that if equal amounts of fertilizer are applied to each St. Augustinegrass, Bahiagrass, and zoysiagrass, then when water is applied at two different time intervals St. Augustine will filter the most fertilizer in both time periods.

Materials and Methods

In order to conduct this experiment there were 8-5 gallon buckets and 8 inserts in the buckets to keep the piece of sod slightly elevated above the water that was poured over them. In addition, we put a piece of window screen was put under the sod pieces in order to keep dirt particles from getting into the bucket and water samples. Next 8 pieces of sod measured to fit the circumference of the buckets for all three ground covers (St. Augustinegrass, Bahiagrass, and Zoysiagrass). In order to conserve materials the experiment was ran on one sod type at a time over the course of three days.

The basic experimental structure is demonstrated in figure 4. This experiment was replicated two times for all of the sod types. Excluding the controls, the pieces of ground cover received 2 grams of fertilizer applied of the most common turf fertilizer used on campus, which is Turf Care 16-0-8 Pendulum pre-emergent. After the fertilizer was applied, each bucket was immediately watered with a gallon of water using a watering can with a rain head attachment and waited 20 minutes before collecting an 8 oz. water sample from each bucket. Then, after 8 hours, the four 8 hour buckets were watered with one gallon, and after 20 minutes water samples were collected from each bucket and immediately tested for the presence of N. The same procedure was repeated with the four 24 hour buckets, after 24 hours from the start of the experiment.-Immediately after collection each water sample was tested for the presence of nitrogen using a YSI (Ecosense 9500 photometer). In order to be able to compare the water after being applied to sod we took 2 grams of fertilizer and dissolved it in 1 gallon of water and also plain water with no fertilizer and tested for the amount of nitrogen present. The results from the collections after 8 hours and 24 hours were multiplied by two to account for the extra gallon of water present in the bucket.

	St. Augustine Control (No fertilizer)	St. Augustine Fertilizer Applied	Bahia Control (No fertilizer)	Bahia Fertilizer Applied	Zoysia Control (No fertilizer)	Zoysia Fertilizer Applied
Time Since Application						
8 Hours	2x	2x	2x	2x	2x	2x
24 Hours	2x	2x	2x	2x	2x	2x

Figure 4. Experimental Structure

Results

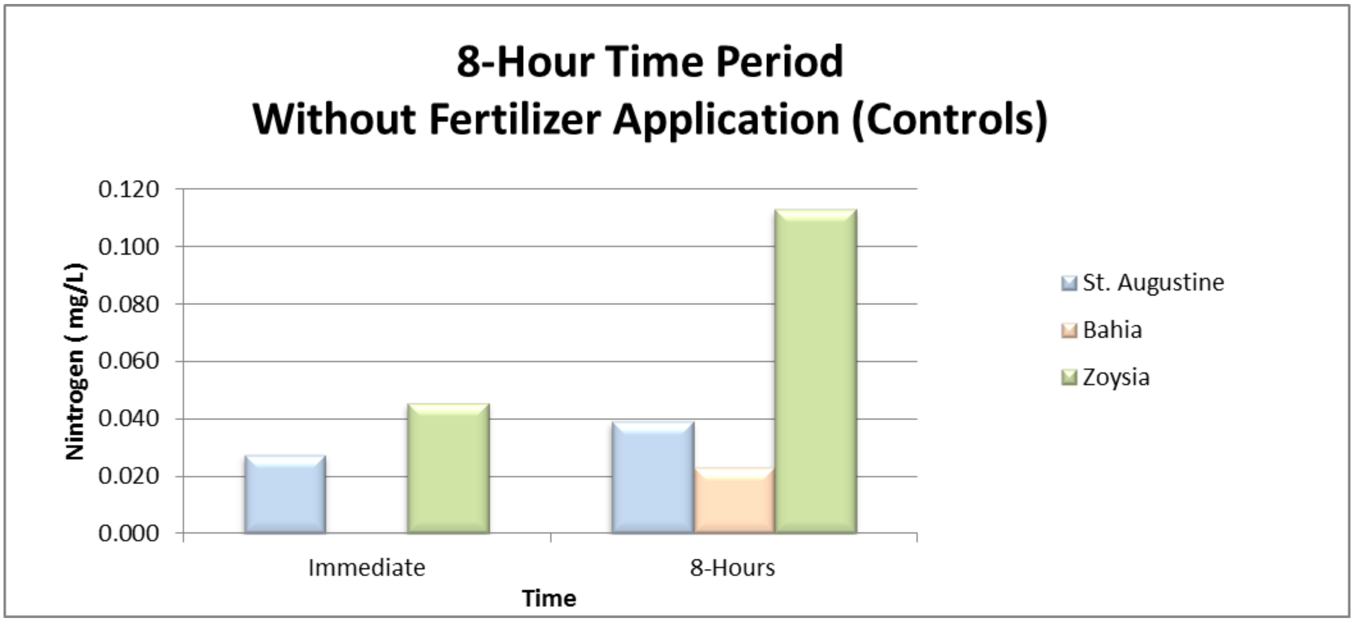


Figure 5. Difference in the amount of nitrogen in the water supply immediately and after 8-hours in the control buckets for St. Augustinegrass, Bahiagrass and Zoysiagrass**.**

Table 1. Percentage change in nitrogen in the buckets without fertilizer application and in the buckets with fertilizer application over the 8-hour time period for three grass species

Percentage Change in Nitrogen at 8-Hours		
Grass Species	**Without Fertilizer**	**With Fertilizer**
St. Augustinegrass	41.82%	40.35%
Bahiagrass	2200.00%	1500.00%
Zoysiagrass	148.35%	55.14%

Figure 5 shows the amount of nitrogen in the control buckets immediately after initial watering and after 8 hours watered again. This figure shows the amount in the control buckets was different among St. Augustinegrass, Bahiagrass and Zoysiagrass in the beginning even without fertilizer application by the scientists. After 8-hours, the nitrogen amount increased in those buckets for all three of the grass species (Figure 5). This trend was also observed when the percentage change in nitrogen was calculated after 8 hours, Table 1 shows that there was a percentage increase in the buckets without added fertilizer. St. Augustinegrass had the smallest percentage increase over the 8-hour time period in the control buckets (Table 1).

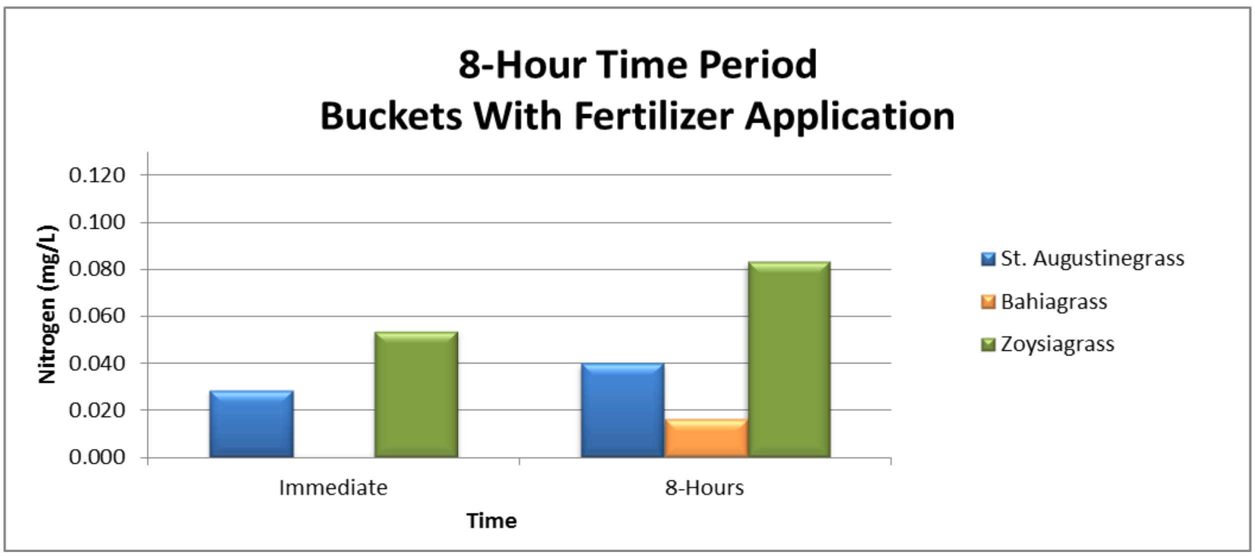


Figure 6. Difference in the amount of nitrogen in the water supply found immediately and after 8-hours in the buckets with fertilizer application for St. Augustinegrass, Bahiagrass and Zoysiagrass.

Similar trends were found in the buckets with added fertilizer after the 8-hour period. For one, the nitrogen amount measured immediately after applying fertilizer and water was different for all the grass species (Figure 6). Furthermore, at the immediate measurement, Bahiagrass showed the least amount of nitrogen in the water supply (Figure 6) which is consistent with the findings in Figure 5. In addition, after 8-hours, the amount of nitrogen increased in the buckets with fertilizer for all three grass species (Figure 6). St. Augustinegrass had the smallest percentage change in the buckets with applied fertilizer, which is consistent with the findings in the control buckets (Table 1). Table 1 also shows that when the percentage change in nitrogen amounts was compared over the 8-hours between the buckets without fertilizer and the buckets with fertilizer it was concluded that the percentage increase of nitrogen was smaller in the buckets with fertilizer application.

Table 2. F-Test two-sample for variances between St. Augustinegrass and Bahiagrass at 8-hours

	St. Augustine	*Bahiagrass*
Mean	0.02425	0.0045
Variance	0.000607583	0.000041
Observations	4	4
df	3	3
F	14.81910569	
P(F<=f) one-tail	0.026464491	
F Critical one-tail	9.276628153	

Due to the fine particulate dirt substrate that the Zoysiagrass was grown on, the photometer did not give accurate results for this species after initial water application. Therefore, this species was left out of statistical analysis. First, in comparing St.augustinegrass and Bahiagrass, an F-Test two-sample for variances between the two grasses for the 8-hour time period was ran to measure how far the set of numbers was spread. The F-test results indicated the variances between these two grass species were significantly different for fertilizer application after 8-hours (P= 0.02646) (Table 2).

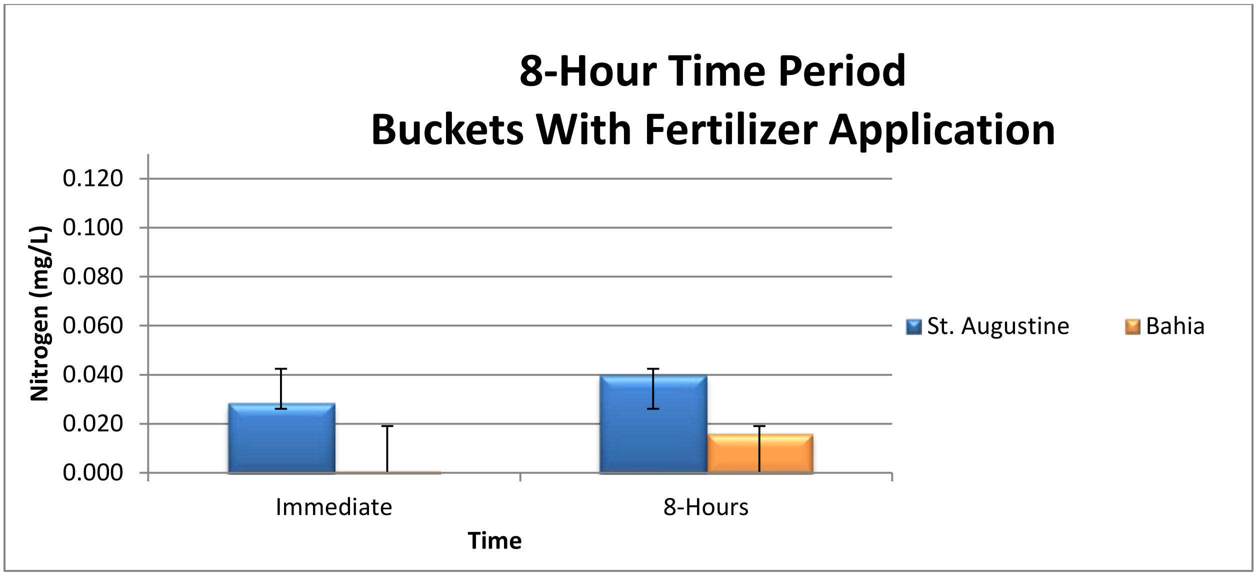


Figure 7. Difference in the amount of nitrogen in the water supply found immediately and after 8-hours in the buckets with fertilizer application for St. Augustinegrass and Bahiagrass, and displaying error bars with standard deviation.

The error bars with standard deviation show in Figure 7 corroborate the trend found with the F-test. The nitrogen amount found immediately as well as the nitrogen amount found after 8-hours was statistically different between St Augustinegrass and Bahiagrass (Figure 7).

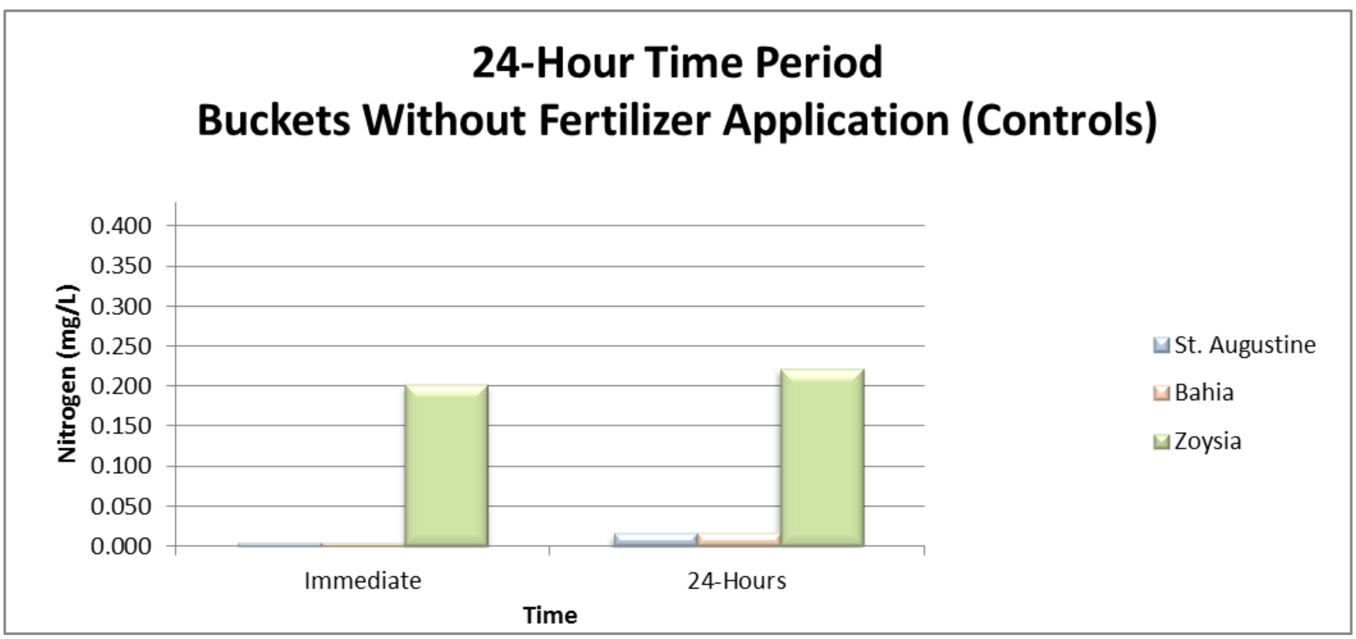


Figure 8. Difference in the amount of nitrogen in the water supply found immediately and after 24-hours in the control buckets for St. Augustinegrass, Bahiagrass and Zoysiagrass.

Table 3 Percentage change in nitrogen in the buckets without fertilizer application and in the buckets with fertilizer application over the 8-hour time period for 3 grass species

Percentage Change in Nitrogen at 24-Hours		
Grass Species	**Without Fertilizer**	**With Fertilizer**
St. Augustinegrass	255.56%	448.39%
Bahiagrass	255.56%	303.77%
Zoysiagrass	9.90%	-57.88%

The nitrogen amount measured immediately after applying one-gallon of water in the 24-hour control buckets was different among St. Augustinegrass, Bahiagrass and Zoysiagrass (Figure 8). Figure 8 shows that after 24-hours when the buckets were watered, the nitrogen amount increased slightly in those buckets without fertilizer application for the three grass species.

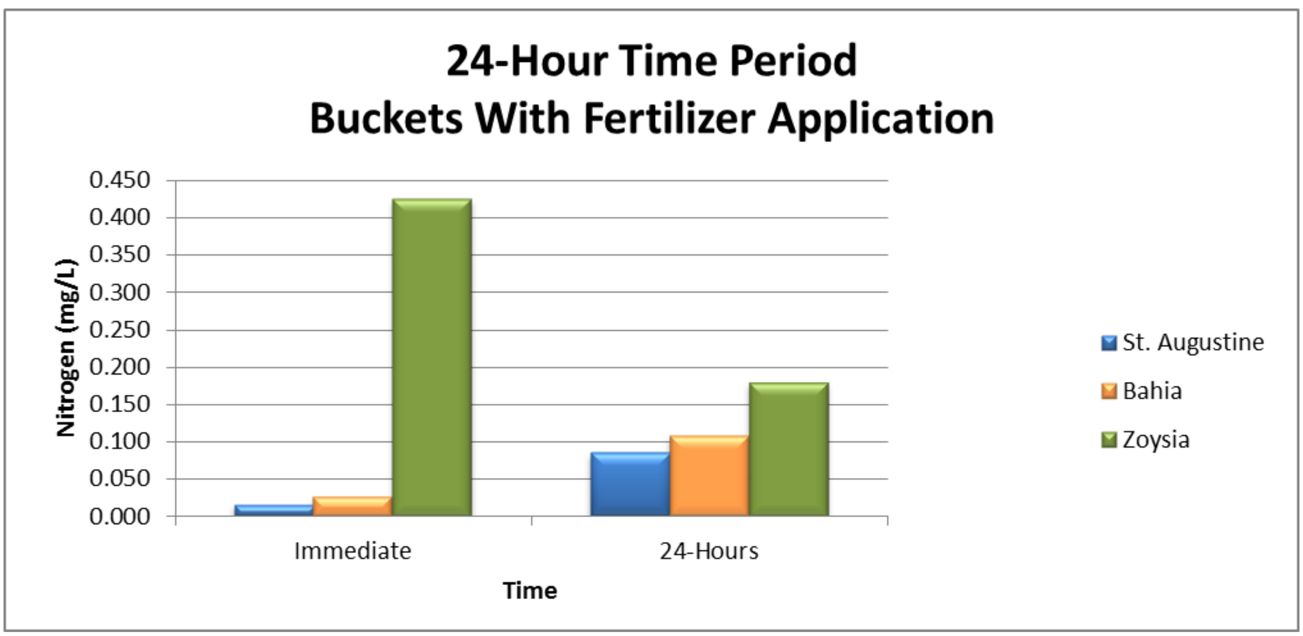


Figure 9. Amount of nitrogen in the water supply found immediately and after 24-hours in the buckets with fertilizer application for St. Augustinegrass, Bahiagrass and Zoysiagrass.

After immediate fertilizer and water application in the 24-hour buckets, the nitrogen amount in the samples was different for all the grass species (Figure 9). Again, the trend in Zoysiagrass was different than the trend found for the two other grass species. The amount of nitrogen in Zoysiagrass decreased over the 24 hours (Figure 9). It was observed that at 24 hours the percentage change in nitrogen decreased by almost 58% in the Zoysiagrass buckets with fertilizer and was the only negative number found in the experiment, these results were considered inconclusive and not used in data analysis(Table 3). St. Augustinegrass and Bahiagrass had an increase in nitrogen after 24 hours (Figure 9). Bahiagrass had the smallest percentage change over the 24-hour time period in the buckets in which fertilizer was applied (Table 3).

Table 4. F-Test Two-Sample for Variances for St. Augustinegrass and Bahiagrass at 24-hours

	St. Augustine	*Bahiagrass*
Mean	0.029	0.042
Variance	0.000563333	0.000721
Observations	4	3
df	3	2
F	0.781322238	
P(F<=f) one-tail	0.396366943	
F Critical one-tail	0.104689082	

For the statistical analysis the F-Test two-sample for variances for St. Augustinegrass and Bahiagrass at 24-hours indicated the variances between these two grass species were not significantly different (P= 0.3963) (Table 4).

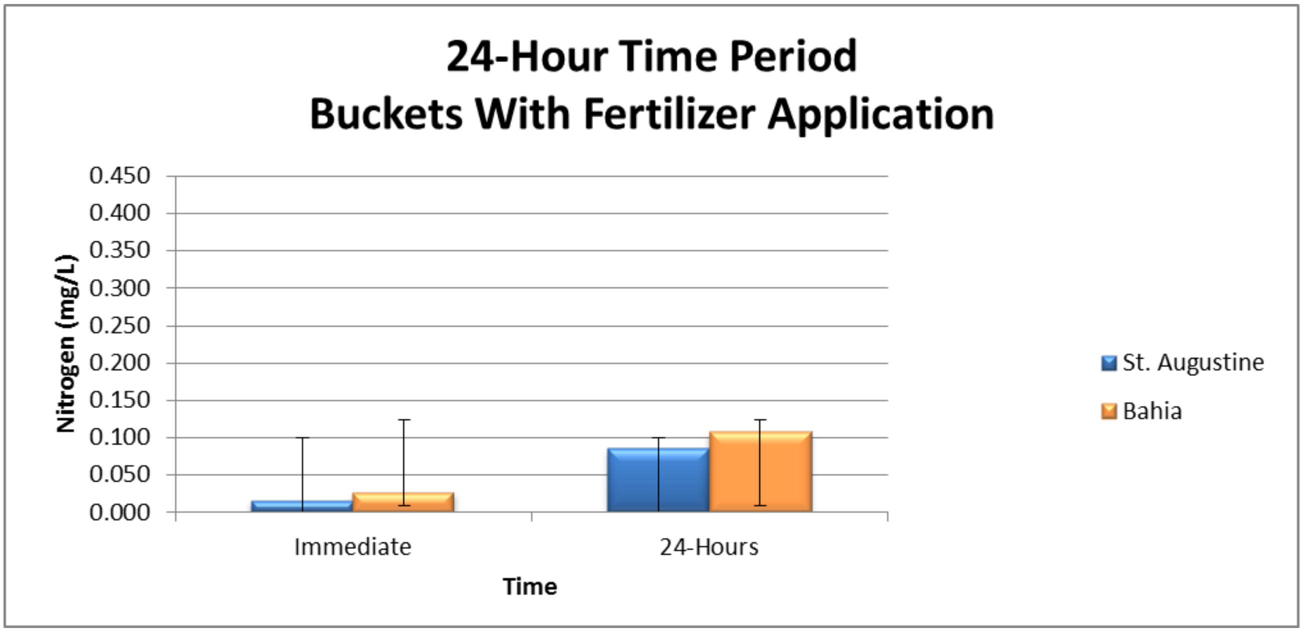


Figure 10. Graph showing the amount of nitrogen in the water supply found immediately and after 24-hours in the buckets with fertilizer application, and displaying error bars with standard deviation for St. Augustinegrass and Bahiagrass.

The error bars with standard deviation corroborate the trend found with the F-test for variances. When the nitrogen amounts found immediately as well as the nitrogen amounts found after 24-hours for St Augustinegrass and Bahiagrass were compared it was concluded that the nitrogen amounts found were not statistically different (Figure 7).

Discussion

This experiment in sustainable ground covers gave results comparable with the hypothesis and results that were extraneous to statistical analysis. Interestingly, every un-fertilized control plot, regardless of grass species, showed increased N leaching over time. The results show that the grasses were all previously fertilized, but at different levels due to coming from different providers. The smallest percentage change in N occurred in the 8 hour time period with St.Augustinegrass (Table 1). This means that of the three grasses, St. Augustine leached the least amount of N. We conclude that St. Augustine will minimize N leaching into groundwater, and will do this most efficiently if watered after 8 hours, and not 24. Our results show that of the three grasses, St.Augustinegrass is the most sustainable lawn cover if only the filtration of nitrogen is a consideration.

The 24 hour time period experiment was exclusive to the 8 hour time period, meaning the buckets tested at each interval were separate from each other and the results for each time must be discussed separately. With the 24 hour period for the three types of turfgrass, the results concluded that Bahiagrass and St.Augustinegrass both had the same percentage change in N leaching for the control plots that had no fertilizer added (Table 3). This means the Bahia and St. Augustine controls filtered N at the same rate over 24 hours, while Zoysiagrass gave inconsistent and extraneous results in both the control and experimental (fertilized) plots. In the fertilized plots, Bahiagrass showed the least amount of N leaching over a 24 hour period, followed closely by St.Augustinegrass (Table 3). These results confirm that while St.Augustine filtered N the best at an 8 hour interval, over the 24 hour time interval, Bahia proved to filter N better than St. Augustine. These results confirm a previously quoted author that stated that St.Augustine requires more fertilizer and water, while Bahiagrass requires less fertilizer and watering (Trenholm 2013). So while St.Augustine did filter out more fertilizer, that is because it requires more fertilizer and more often, and this may not make it the most sustainable choice for a groundcover.

Zoysiagrass' measurements were overall inconsistent due to its different substrate and how the photometer measured its N levels. The samples were not read accurately by the photometer, which uses light to measure changes in coloration from a dissolved nitrogen reagent. Bahia and St. Augustine both had visibly sandier substrates and their water samples were noticeably clearer. If the Zoysiagrass were grown on a sandy substrate like the other grasses then possibly it would show trends more similar to Bahia and St. Augustine's ability to filter out N.

Application of Research

Our findings are important when considering the immense acres of land that are, and will be, covered by one of these common turfgrasses. Take for example an upscale community that is centered around a well-kept golf course. The grounds must be maintained and fertilized to an extent where the groundwater below is continually being leached into. These communities are unsustainable in their current use of ground covers. This example of expanded turfgrass cover can also be applied to large sports complexes which will commonly be developed near sprawling communities. They too cover large amounts of acreage with planted grasses and are consistently watered and fertilized. Our research hopes to balance out this desire for expansive covers of turfgrass and the need for a sustainable choice. Another example is the grassy shoulder of roadways. These are usually roads that cut through natural habitats and have planted sods just off their sides on the right and left shoulders. Although these grasses may not be fertilized after they're planted, it is evident from our research (specifically our control plots) that all planted turfgrasses have been fertilized before and will leach N when water is applied.

There are certain harms associated with excess N in natural systems. Lakes are commonly "aged" by excess amounts of nitrates in a process called eutrophication which depletes oxygen levels and kills off fish. Likewise newborn babies are susceptible to a condition known as "blue baby syndrome" if excess nitrates contaminate the water supply for drinking. Each of these examples involves the inability for inorganic nitrogen to properly decompose over time ("Frequently asked questions," 2013). Evidence has shown that exposure to chemicals used in lawn care may result in cancer, respiratory problems, skin rashes, and memory failure. (Keesling,

2003) These examples are known hazards from high levels of N and a more sustainable practice in ground cover may prevent these negative effects of fertilizer use.

The most sustainable method for fertilization is socially promoting organic fertilizer use which better facilitates nitrogen decomposition and promoting continual sustainable research. The existing body of knowledge is very specific in its focus and our findings can facilitate research done previously on Zoysia, St. Augustine, and Bahia grasses. Two recent studies are specific for these grasses, but they only focus on phosphate leaching and lack specific enough details on nitrogen leaching to be a comprehensive body of knowledge (Gonzales et al., 2013; Obour et al., 2010). Our research is needed to accompany the existing findings so that the most effective and sustainable body of knowledge can be used to prevent environmental damages.

The researchers have several suggestions for how to better this experiment for more accurate results and better understanding. For example, in this experiment the researchers did not have access to grass that had come from one provider and without the previous use of fertilizer and a consistent substrate. If all three grasses had the same substrate and a level of 0 mg/l N to begin, then this experiment would have yielded more accurate and useful results. A greater amount of time intervals would also be able to provide a more broad view of when is the best time to water a lawn after applying fertilizer. The research would also have benefitted from more replicates within each time period as the experiment only included two replicates.

Further research is needed in this very important area in order for people and their desire for residential homogeny to coexist with a healthy planet.

Works Cited

Andrews, M., & Lea, P. J. (2013). Our nitrogen 'footprint': the need for increased crop nitrogen use efficiency. *Annals of Applied Biology*, *163*(2), 165-169.

Bormann, F.H., Balmori, D., et al., 1993. Redesigning the American Lawn. Yale University Press, New Haven.

Callicott, J. B. & Mumford, K. (1997) Ecological sustainability as a conservation concept. *Conservation Biology*, 11, 32-40.

Cisar, J.L, Erickson, J.E., Snyder, G.H., Volin, J.C. 2001. Comparing nitrogen runoff and leaching between newly established St. Augustinegrass turf and an alternative residential landscape. *Crop Science, 41.6*, 1889.

Erickson, John E., Volin, John C., Cisar, John L., Snyder, George H. 1999. A facility for documenting the effect of urban landscape type on nitrogen runoff. *Proc. Fla. State Hort. Soc.*, *112*, 266-269.

Farber, S., et al. (2006). Linking ecology and economics for ecosystem management. *BioScience,* 56(2), 121.

Florida Department of Environmental Protection. 2007. Aquifers. Accessed 9/24/2013. http://www.dep.state.fl.us/swapp/aquifer.asp

Frequently asked questions. (2013, August 13). Retrieved from http://water.usgs.gov/owq/FAQ.htm

Gonzales, R., Sartain. J., Kruse, J., Obreza, T., O'Connor, G., Harris, W. (2013). Orthophosphate Leaching in St. Augustinegrass and Zoysiagrass Grown in Sandy Soil under Field Conditions. *JOURNAL OF ENVIRONMENTAL QUALITY*, *42*(3), 749-757. DOI: 10.2134/jeq2012.0233

Keesling, G., & Kaynama, S. A. (2003). An exploratory investigation of the ecologically conscious consumer's efforts to control water contamination: lawn care and the use of nitrogen fertilizers and pesticides. *Journal Of Marketing Theory & Practice*, 11(1), 52.

McDonald, R. I., Douglas, I., Revenga, C., Hale, R., Grimm, N., Groenwall, J., & Fekete, B. (2011). Global urban growth and the geography of water availability, quality, and delivery. *Ambio*, *40*(5), 437-446.

Miller, J. A. (1990). Floridan Aquifer System. *USGS*. HA 730-G. Accessed 9/23/2013. http://pubs.usgs.gov/ha/ha730/ch_g/G-text6.html

Obour, K., Silveira, M., Vendramini, J., Sollenberger, L., O'Connor, G., Jawitz, J. (2010). Agronomic and environmental impacts of phosphorus fertilization of low input bahiagrass systems in Florida. *Nutrient Cycling in Agroecosytems*, *89*(2), 281-290

Puckett, Larry J., Tesoriero, Anthony J., & Dubrovsky, Neil M. 2011. Nitrogen contamination of surficial aquifers- a growing legacy. *Environmental Science and Technology*,*45*,839-844.

Raciti, S., Groffman, P., Jenkins, J., Pouyat, R., Fahey, T., Pickett, S., & Cadenasso, M. (2011). Nitrate production and availability in residential soils. *Ecological Applications*, 21(7), 2357-2366.

Robbins, P., & Birkenholtz, T. (2003). Turgrass revolution: Measuring the expansion of the American lawn. Land Use Policy, 20(2), 181-194.

Robertson, G.P., Vitousek, P.M., 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. *Annu. Rev. Environ. Resour.* 34, 97–125.

Stiglbauer, J., Liu, H., McCarty, L., Park, D., Toler, J., & Kirk, K. (2009). 'Diamond' Zoysiagrass Putting Green Establishment Affected by Sprigging Rates, Nitrogen Sources, and Rates in the Southern Transition Zone. *Hortscience*, 44(6), 1757-1761

Trenholm, L. E., Cisar, J. L., Unruh, J. B. (2013). St. Augustinegrass for Florida Lawns. *University of Florida IFAS Extention.* September 23, 2013. http://edis.ifas.ufl.edu/lh010.

Trenholm, L. E., Unruh, J. B., & Sartain, J. B. (2013). *Nitrate leaching and turf quality in newly sodded st. Augustine*. Informally published manuscript, University of Florida, Gainsville, Florida, Available from Taylor Francis Online.

Van Beynen, P., Niedzielski, M., Bialkowska-Jelinska, E., Alsharif, K., & Matusick, J. (2011). Comparative study of specific groundwater vulnerability of a karst aquifer in central Florida. *Applied Geography*, *32*(2), 868-877.

Whitney, K. (2010). Living lawns, dying waters: the suburban boom, nitrogenous fertilizers, and the nonpoint source pollution dilemma. *Technology And Culture,* (3), 652. doi:10.2307/40927990