Quantifying the Potential for Non-Point Source Pollution in Model Urban Landscapes

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Abstract

The contribution of non-point source pollution to degrading surface water quality is considerable throughout Virginia and beyond. While research on agricultural best management practices in nutrient management and nutrient and soil stabilization has made progress in reducing agricultural contributions to nutrient and sediment loading of watersheds, little is known about how land covers of different vegetation representative of urban areas (e.g., bare soil versus turfgrass lawns versus urban forest) influence the potential for non-point source pollution.

Ambient rainfall volumes were manipulated to provide 50%, 100%, and 150% of natural precipitation to plots with landscape covers of bare soil, shredded wood mulch, turfgrass, and simulated urban forest (complete pin oak canopy with shredded hardwood leaf mulch). Precipitation amounts, runoff volumes, and eroded sediment masses for ten rain events between July and December 2004 were measured. Runoff was analyzed for nitrate and orthophosphate concentrations for three rain events. Turfgrass was found to be the most effective of the land covers tested at reducing components of non-point source pollution from stormwater. Turfgrass plots produced, on average, the least runoff and sediment, and lower nitrate concentrations in runoff water as compared to the other land covers tested. Results from urban forest plots apparently reflected the disturbance of tree planting, even six months later. This study contributes to a sparse body of knowledge about the influences of urban landscapes on water quality, and will inform land use policy and urban Best Management Practices.

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Chapter 1

Literature Review

The negative effects of excessive nutrient and sediment loading to surface waters have been well documented. While agricultural land uses make up a substantial portion of non-point source pollution to surface waters, urban areas also contribute to the degradation of water quality (Coulter *et al*. 2004). In 2003, it was reported that overall water quality in the Chesapeake Bay declined in the previous year largely as a result of increased nitrogen, phosphorus, and sediment loading to surface waters from urban landscapes after record heavy rainfalls (Chesapeake Bay Foundation 2003). The rate of urban and suburban development continues to be high, taking away valuable forests, farms, and wetlands that play an important role in slowing and filtering stormwater runoff (Chesapeake Bay Foundation 2004). These trends are mirrored nationally in nearly every watershed impacted by rapid urbanization, with N inputs into estuaries now reported at rates up to 20 times greater than in pre-industrialized times (Castro *et al*. 2003). This has created a need for a more detailed understanding of how urban and suburban areas can negatively impact water quality.

Nutrient and sediment runoff from agricultural as well as urban landscapes contributes to water quality impairment via adverse consequences to the biological and physical environment. Excessive N and P loading can cause eutrophication of surface water bodies. Total N and P concentrations in surface waters as low as 1 mg L^{-1} and 25 µg L^{-1}, respectively, can produce algal blooms to the serious detriment of aquatic ecosystems (Baird *et al.* 2000). Increases in sediment runoff, in addition to algal blooms, create excessively shady conditions, blocking out light needed by aquatic vegetation. As a result, there is a reduction in these vegetative stands that serve as food and shelter for many other aquatic organisms. Algal blooms also contribute to increased biochemical oxygen demand and reduced oxygen supply. Oxygen deficiency reduces the capacity of aquatic ecosystems to support biological activity, resulting in decreased populations of fish and other organisms (Castro *et al*. 2003, Easton and Petrovic 2004). The physical environment also changes with excessive nutrient and sediment loads, affecting hydrology and water chemistry, leading to overall decreases in water quality (Basnyat *et al*. 1999).

In addition to the negative impacts non-point source pollution can have on aquatic ecosystems, human health can also be affected. Nitrates can be a health hazard in potable water sources. The U.S. Environmental Protection Agency (USEPA) has set 10 ppm as an upper limit for NO_3-N in drinking water (Cisar *et al.* 2004). Surface waters affected by excessive nutrients and sediment also face limited use by humans for recreation. The USEPA reports that 53% of rivers and streams and only 47% of lakes, reservoirs, and ponds are fully supporting of human uses. This suggests that the remaining water bodies are not safe for all of their designated uses (i.e. swimming, fishing, drinking; USEPA 2002).

Agricultural land use is considered the greatest contributor to non-point source pollution of surface and ground water. The USEPA reports 41% of the NPS pollution load to lakes, reservoirs, and ponds and 48% to rivers and streams results from agricultural activities (USEPA 2002). Among the pollutants produced by these activities are sediments, animal wastes, plant nutrients, crop residues, inorganic salts and minerals, and pesticides (Basnyat *et al*. 1999). This large contribution to the NPS pollution load is evidenced by comparison to forested or natural areas. Mathan and Kannan (1993) found that losses of N, P, and sediment were greater under agricultural rather than forest conditions. Rai and Sharma (1998) found increased losses of N and P and increased sediment erosion as forested land was converted to agricultural land over a three year period, suggesting that forest cover was needed for ecological sustainability of the watersheds studied. Research comparing agricultural watersheds to urban watersheds also shows higher rates of N and P loss from agricultural areas. A study in Kentucky found that more nitrates and orthophosphates were lost from agricultural watersheds than from their urban counterparts (Coulter *et al*. 2004).

While agricultural lands contribute close to half of all NPS pollution, there are other significant sources of this pollution. Among other contributors are urban runoff and storm sewers, reported as one category by the USEPA as contributing 18% to lakes, reservoirs, and ponds and 13% to rivers and streams (USEPA 2002). Urban landscapes are a complex matrix of different land cover types including impervious surfaces, lawns, open fields, bare soils and urban forest fragments of varied structure. Land cover type influences the ability of soils to allow infiltration of precipitation versus contributing to runoff. In order to better understand NPS pollution from urban areas, it is necessary to study the capacity of different land use components of urban areas to influence hydrology.

The propensity for turfgrass to mitigate runoff and facilitate infiltration has been studied in some detail, particularly in relation to golf courses. Petrovic (1990) reviewed the literature on N fertilizer use on turfgrass and reported that, in previous studies, up to 53% of applied N was leached, depending on management practices. In addition, Petrovic (1990) reported that little runoff from turfgrass under natural precipitation was observed in previous studies, indicating a high infiltration capacity. However, comparisons of fertilized turfgrass to an unfertilized control turfgrass showed significantly higher runoff of N from fertilized turfgrass (Gross *et al*. 1990). In this study, plots previously cropped to tobacco were sodded with a mix of tall fescue (*Festuca arundinacea* Schreb.) and Kentucky bluegrass (*Poa pretensis* L.). The plots were fertilized with liquid and granular fertilizers at a rate of 220 kg N ha^{-1} yr^{-1} or left as unfertilized control plots.

More recently, in a study comparing N and P concentrations of irrigation water and surface runoff on a municipal golf course, significantly higher N levels were recorded in runoff (King *et al*. 2001). This study conducted in Austin, Texas, used a hydrologically isolated area of the golf course with bermudagrass (*Cynodon dactylon* L. Pers.) overseeded in late fall with perennial ryegrass (*Lolium perenne* L.). Despite increased N content in runoff, it did not exceed nutrient screening thresholds, but the authors suggested better management should be implemented to reduce N losses. In a different study on simulated golf fairways with creeping bentgrass (*Agrostis palustris* Huds.) and perennial ryegrass, runoff of NO_3 and NO_2 from turfgrass was reported to be 2% of applied N on average while 11% of applied P left the site in runoff (Linde and Watschke 1997). In contrast, King *et al*. (2001) reported no change in P concentrations in water applied versus water runoff collected. Linde *et al*. (1995, 1998) studied runoff in two common golf course turfgrasses and concluded creeping bentgrass was more effective in reducing runoff than perennial ryegrass.

Although the contribution of both N and P to nutrient runoff in managed landscapes is often highly dependent on fertilization management, transport of P is usually closely tied to sediment erosion. Consequently, nutrient loading of surface waters from urban and suburban landscapes is highly variable due to many factors including soil type, vegetation cover, and management practices (Petrovic 1990). However, under proper management practices with correct fertilizer applications, there generally is no excessive nutrient loss (Easton and Petrovic 2004).

The apparent ability of turfgrass to facilitate infiltration and mitigate runoff has made it appealing as a buffer strip material to filter out excessive nutrients in runoff. The dense growth habit of turfgrass and the production of thatch create a tortuous pathway that slows runoff, reduces sediment loss, and increases infiltration (Linde *et al*. 1995, 1998).

Vegetated buffer strips including turfgrass and other vegetation (mixed herbaceous and woody perennials) have been widely implemented and studied to control NPS pollution in runoff from agricultural fields and forestry operations (i.e. clear cutting; Norris 1993, Baird *et al*. 2000, Arora *et al*. 2003). These buffers reduce runoff by slowing it down, allowing for increased infiltration, physically filtering sediments and chemicals (Baird *et al*. 2000). Schmitt *et al*. (1999) reported reductions in runoff sediment concentration between 76% and 93% from 7.5 and 15 m wide filter strips containing sorghum [*Sorghum bicolor* (L.) Moench], grass, or a mix of young trees and shrubs with grass. This reduction in sediment also led to a reduction in contaminants strongly associated with sediment, including a reduction of total P concentrations by 55-79%. Concentrations of dissolved contaminants were reduced as well, with a 24-48% reduction in nitrate concentrations (Schmitt *et el*. 1999).

The width of vegetative filter strips can have an impact on how effective they are in reducing runoff and pollutant loss. Experiments on grass filter strips have shown that a 4.6 meter width will retain 53-86% of sediment, but little more is retained (4-17%) by doubling the width (Schmitt *et al*. 1999). Thus, in experiments where filter strips of various widths greater than 4.6 meters were tested, no significant improvement in sediment retention was found with increasing filter strip widths (Srivastava *et al*. 1996, Schmitt *et al*. 1999). An experiment comparing shorter widths found there were generally no significant differences in runoff or pollutant losses from filters strips of 1.2, 2.4, and 4.9 m in width, but all were significantly more effective than the non-buffered treatments. In this case, mowing height of the grass within the filter strips had a greater influence than width, where higher mowing heights were more effective in reducing runoff and pollutant losses (Baird *et al*. 2000).

Other factors besides width and mowing height can influence the effectiveness of vegetative filter strips. In particular, the vegetation used in the filter strips and the pollutants targeted for control will influence filter strip effectiveness. Different pollutants act differently in runoff and are affected in different ways by the various pollutant removal mechanisms in filter strips, such as settling, infiltration, and dilution (Schmitt 1999). For example, inorganic fertilizer sources of N and P in runoff were reduced 94 and 98%, respectively. In contrast, N and P from organic cattle manure sources were only reduced 75 and 10%, respectively, by grass filter strips (Heathwaite *et al*. 1998).

The mechanisms that reduce pollutant runoff likely vary according to vegetation type, affecting the impact of a filter strip on the reduction of various pollutants. For example, grass filter strips were found to be more effective at reducing sediment and associated pollutants compared to filter strips cultivated with sorghum, but both grass and sorghum plots showed similar amounts of runoff and dissolved pollutants. The addition of trees and shrubs in the lower portion of grass filter strips was found to have no impact on performance compared to grass only filters (Schmitt 1999).

Research has resulted in implementation of vegetative filter strips and other Best Management Practices (BMPs) in agricultural settings that have been successful in reducing NPS pollution. However, little research has addressed the use of vegetative buffers in urban and suburban areas. Research that has addressed urban NPS pollution indicated that urban and mixed-use (urban and agricultural) watersheds were subject to increased total suspended solids (TSS), turbidity, temperature, and pH, while nitrate and orthophosphates did not pose as great a risk as in agricultural watersheds (Coulter *et al*. 2004). A study of major land uses in Florida indicated sediment and nutrient losses were closely related to land use and how much fertilizer was applied (Graves *et al*. 2004). In a modeling effort to estimate the influence of changes in land use on nitrate runoff, conversion of a forested area to a golf course increased nitrate loading in runoff, while conversion of agricultural land to golf course use decreased nitrate loading. However, this model did not include the addition of housing developments and increased impervious areas, which typically accompany golf course development and produce increased risk potential for runoff losses (King and Balogh 2001).

Because urban landscapes are a complex matrix, with small patches of different land cover types woven together in random and regular patterns, studying urban NPS pollution can be difficult. Making things more complicated are the numerous land owners using various land management practices. Surveys of homeowners indicate a general lack of knowledge of proper landscape management practices (Carpenter and Meyer 1999, Varlamoff *et al*. 2001, Osmond and Hardy 2004). In a survey in Edina, Minnesota, fewer than 6% of respondents knew how much fertilizer should be applied to medium maintenance lawns on a yearly basis (Carpenter and Meyer 1999). A 1989 report from the National Academy of Sciences indicated homeowners used as much as 10 times more chemicals per acre on their lawns compared to agricultural lands (Jenkins

1994). This heavy application of chemicals can be largely attributed to the popular belief that more is better (Varlamoff *et al*. 2001).

Homeowners apply fertilizers and pesticides in hopes of meeting expectations set forth in popular culture (Jenkins 1994). In a survey of Georgia homeowners, 56% of respondents indicated it was at least “somewhat important” to maintain a green lawn year-round. In addition, 54% of respondents in this survey expressed a desire for their lawns to match the quality of other lawns in their neighborhood (Varlamoff *et al*. 2001). Also driving the intense maintenance of these urban and suburban lawns are economic reasons. In Virginia, a 1981 survey of homeowners found 70% of respondents were not satisfied with the current state of their lawns. Almost all (95%) of the respondents thought that well-kept and improved lawns and landscapes increased the dollar value of their properties (Latimer *et al*. 1996).

While a lack of knowledge on the part of homeowners often leads to overuse of fertilizers and pesticides, the contributions these chemicals make to NPS pollution is compounded by overwatering. Surveys of homeowners have indicated that, in addition to overuse of fertilizers and pesticides, water tends to be used in excessive quantities (Weaver 1993, Osmond and Hardy 2004). This excess water applied to the landscape can run off or percolate from the landscape, increasing the amount of sediment, nutrients, and other pollutants that are loaded to water systems. A survey conducted in Perth, Australia reported that homeowners applied more than twice the recommended quantity of water for healthy turf. The majority of these homeowners were found to apply three or more times the recommended quantity of water (Weaver 1993). Investigation of water use in the Town of Cary, North Carolina suggested that homes with installed irrigation systems used twice the amount of water compared to residents who used moveable sprinklers, increasing the chances of N leaching from properties with installed irrigation (Osmond and Hardy 2004).

Given the results of these homeowner surveys, it is clear that there is a need to communicate information on BMPs and other environmentally sound urban and suburban landscape maintenance practices to homeowners. A survey of Albuquerque, New Mexico homeowners indicated that 17% of home owners received maintenance information from nurseries, while all other sources (university and extension, books and magazines, television, landscape professionals, etc.) were each used less than 14% of the time. In California, 22% obtained information from nurseries, while only 2% used university extension services. Both of these surveys suggested a need for universities and extension services to produce educational programs for sales professionals to allow them to pass environmentally sound information onto consumers (Latimer *et al*. 1996).

Other university extension programs have been used to directly educate homeowners on BMPs that reduce the environmental impact of urban and suburban landscapes. Programs, such as the Florida Yards and Neighborhoods (FYN) program, have included water quality and surface runoff among the many issues they address. In reaching its goals of improved water quality and water and energy conservation, FYN encourages the use of alternative landscape materials. While this is suggested primarily as a method of resource conservation, it is thought these alternative materials may provide other environmental benefits, such as reducing nutrient runoff (Erickson *et al*. 1999, 2001).

However, little research to date has addressed the use of alternatives to turfgrass that require less maintenance and resource inputs, while at the same time reduce the potential for NPS pollution from urban and suburban landscapes. Ongoing research in

Florida has compared runoff and leaching of N, P, and K from St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] with that from a mixed species landscape (trees, shrubs, and herbaceous perennials; Erickson *et al*. 1999, 2001, 2005). Granular nitrogen fertilizer was applied every two months to the turfgrass plots, but only every four months to the mixed species plots. Data on leaching of N from these plots indicated that turfgrass was significantly more effective in reducing the amount of N lost through leaching (Erickson *et al*. 1999, 2001). Phosphorous and potassium were applied with nitrogen fertilizer to turfgrass plots every two months, but were only applied to mixed species plots during establishment. Investigation of P and K leaching showed results similar to N leaching, with turfgrass more effectively reducing nutrient loss (Erickson *et al*. 2005).

While the results of Erickson *et al*. (1999, 2001, 2005) support turfgrass as most effective in reducing nutrient loss from urban and suburban landscapes, additional research investigating alternative landscapes is necessary to fully determine their effectiveness in reducing NPS pollution potential. Research addressing the influence of land cover types in urban landscapes on nutrient and sediment runoff necessitates controlled experimental designs. An innovative design that utilizes alternative landscape land covers in combination with manipulated precipitation volume was used to quantify land use impacts on runoff, potential for sediment erosion, and transport of nutrients from landscapes. Specifically, land covers of bare soil, mulch, turfgrass, and urban forest were compared. The results of this research will improve designs and BMPs that reduce the environmental impacts of urban and suburban landscapes.

Literature Cited

Arora, K., S.K. Mickelson, and J.L. Baker. 2003. Effectiveness of vegetated buffer strips in reducing pesticide transport in simulated runoff. Transactions of the American Society of Agricultural Engineers 46(3): 635-644.

Baird, J.H., N.T. Basta, R.L. Huhnke, G.V. Johnson, M.E. Payton, D.E. Storm, C.A. Wilson, M.D. Smolen, D.L. Martin, and J.T. Cole. 2000. Best management practices to reduce pesticide and nutrient runoff from turf. p. 268-293. In: J.M. Clark and M.P. Kenna (eds.). Fate and Management of Turfgrass Chemicals. American Chemical Society, Washington, D.C.

Basnyat, P., L.D. Teeter, K.M. Flynn, and B.G. Lockaby. 1999. Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. Environmental Management 23(4): 539-549.

Carpenter, P.J. and M.H. Meyer. 1999. Edina goes green part III: A survey of consumer lawn care knowledge and practices. HortTechnology 9: 491-494.

Castro, M.S., C.T. Driscoll, T.E. Jordan, W.G. Reay, and W.R. Boynton. 2003. Sources of nitrogen to estuaries in the United States. Estuaries 26(3): 803-814.

Cisar, J.L., J.E. Erikson, G.H. Snyder, J.J. Haydu, and J.C. Volin. 2004. Documenting nitrogen leaching and runoff losses from urban landscapes. p. 161-179. In: W.L. Hall and W.P. Robarge (eds.). Environmental Impact of Fertilizer on Soil and Water. American Chemical Society, Washington, D.C.

Coulter, C.B., R.K. Kolka, and J.A. Thompson. 2004. Water quality in agricultural, urban, and mixed land use watersheds. Journal of the American Water Resources Association 40(6): 1593-1601.

Chesapeake Bay Foundation. 2004. 2004 State of the Bay Report. Annapolis, MD. Accessed 29 March 2005. http://www.cbf.org/site/DocServer/w33475.pdf?docID=2563

Chesapeake Bay Foundation. 2003. The State of the Bay Report. Annapolis, MD. Accessed 8 December 2003. http://www.cbf.org/site/DocServer/2003SOTBReport.pdf?docID=1201

Easton, Z.M. and A.M. Petrovic. 2004. Fertilizer source effect on ground and surface water quality in drainage from turfgrass. Journal of Environmental Quality 33(2): 645-655.

Erickson, J.E., J.L. Cisar, G.H. Snyder, and J.C. Volin. 2005. Phosphorus and potassium leaching under contrasting residential landscape models established on a sandy soil. Crop Science 45: 546-552.

Erickson, J.E., J.L. Cisar, J.C. Volin, and G.H. Snyder. 2001. Comparing nitrogen runoff and leaching between newly established St. Augustinegrass turf and an alternative residential landscape. Crop Science 41: 1889-1895.

Erickson, J.E., J.C. Volin, J.L. Cisar, and G.H. Snyder. 1999. A facility for documenting the effect of urban landscape type on fertilizer nitrogen runoff. Proceedings of the Florida State Horticulture Society 112: 266-269.

Graves, G.A., Y. Wan, and D.L. Fike. 2004. Water quality characteristics of storm water from major land uses in south Florida. Journal of the American Water Resources Association 40(6): 1405-1419.

Gross, C.M., J.S. Angle, and M.S. Welterlen. 1990. Nutrient and sediment losses from turfgrass. Journal of Environmental Quality 19(4): 663-668.

Heathwaite, A.L., P. Griffiths, and R.J. Parkinson. 1998. Nitrogen and phosphorus in runoff from grassland with buffer strips following application of fertilizers and manures. Soil Use and Management 14: 142-148.

Jenkins, V.S. 1994. The Lawn – A History of an American Obsession. Washington: Smithsonian Institution Press. 246 p.

King, K.W. and J.C. Balogh. 2001. Water quality impacts associated with converting farmland and forests to turfgrass. Transactions of the American Society of Agricultural Engineers 44(3): 569-576.

King, K.W., R.D. Harmel, H.A. Torbert, and J.C. Balogh. 2001. Impact of a turfgrass system on nutrient loadings to surface water. Journal of the American Water Resources Association 37: 629-640.

Latimer, J.G., S.K. Braman, R.B. Beverly, P.L. Thomas, J.T. Walker, B. Sparks, R.D. Oetting, J.M. Ruter, W. Florkowski, D.L. Olson, C.D. Robacker, M.P. Garber, O.M. Lindstrom, and W.G. Hudson. 1996. Reducing the pollution potential of pesticides and fertilizers in the environmental horticulture industry: II. Lawn care and landscape management. HortTechnology 6(3): 222-232.

Linde, D.T. and T.L Watschke. 1997. Nutrients and sediment in runoff from creeping bentgrass and perennial ryegrass turfs. Journal of Environmental Quality 26: 1248-1254.

Linde, D.T., T.L. Watschke, and A.R. Jarrett. 1998. Surface runoff comparison between creeping bentgrass and perennial ryegrass turf. Journal of Turfgrass Management 2: 11-34.

Linde, D.T., T.L. Watschke, A.R. Jarrett, and J.A. Borger. 1995. Surface runoff assessment from creeping bentgrass and perennial ryegrass turf. Agronomy Journal 87: 176-182.

Mathan, K.K. and N. Kannan. 1993. Influence of rainfall on nutrient loss in sediment and runoff water in two watersheds under contrasting landscape systems. Journal of the Indian Society of Soil Science 41(3): 606-608.

Norris, V. 1993. The use of buffer zones to protect water quality: a review. Water Resources Management 7(4): 257-272.

Osmond, D.L. and D.H. Hardy. 2004. Characterization of turf practices in five North Carolina communities. Journal of Environmental Quality 33(2): 656-575.

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. Journal of Environmental Quality 19(1): 1-14.

Rai, S.C. and E. Sharma. 1998. Comparative assessment of runoff characteristics under different land use patterns within a Himalayan watershed. Hydrological Processes 12: 2235-2248.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation, widths, and contaminants. Journal of Environmental Quality 28: 1479-1489.

Srivastava, P., D.R. Edwards, T.C. Daniel, P.A. Moore Jr., and T.A. Costello. 1996. Performance of vegetative filter strips with varying pollutant source and filter strip lengths. Transactions of the American Society of Agricultural Engineers 39(6): 2231-2239.

USEPA. 2002. National Water Quality Inventory: 2000 Report. EPA-841-R-02-001. United States Environmental Protection Agency, Washington, DC.

Varlamoff, S., W.J. Florkowski, J.L Jordan, J. Latimer, and K. Braman. 2001. Georgia homeowner survey of landscape management practices. HortTechnology 11(2): 326-331.

Weaver, D.M. 1993. Managing nutrient losses from rural point sources and urban environments. Fertilizer Research 36: 165-170.

Chapter 2

Quantifying Runoff, Sediment, and Nutrient Losses from Model Urban Landscapes

Abstract

The contribution of non-point source pollution to degrading surface water quality is considerable throughout Virginia and beyond. While research on agricultural best management practices in nutrient management and nutrient and soil stabilization has made progress in reducing agricultural contributions to nutrient and sediment loading of watersheds, little is known about how land covers of different vegetation representative of urban areas (e.g., bare soil versus turfgrass lawns versus urban forest) influence the potential for non-point source pollution.

Ambient rainfall volumes were manipulated to provide 50%, 100%, and 150% of natural precipitation to plots with landscape covers of bare soil, shredded wood mulch, turfgrass, and simulated urban forest (complete pin oak canopy with shredded hardwood leaf mulch). Precipitation volumes, runoff volumes, and eroded sediment masses were measured for ten rain events between July and December 2004. Runoff water was analyzed for nitrate and orthophosphate concentrations in three rain events. Turfgrass was found to be the most effective of the land covers tested in reducing components of non-point source pollution from stormwater. Turfgrass plots produced, on average, the least runoff and sediment, and lower nitrate concentrations in runoff. Results from urban forest plots apparently reflected the disturbance of tree planting, even six months later. This study contributes to a sparse body of knowledge about the influences of urban landscapes on water quality, and will inform land use policy and urban Best Management Practices.

Introduction

The negative effects of excessive nutrient and sediment loading to our water systems have been well documented. While agricultural land uses make up a substantial portion of non-point source pollution to surface waters, urban areas also contribute to the degradation of water quality (Coulter *et al*. 2004). The rate of urban and suburban development continues to be high, taking away valuable forests, farms, and wetlands that play an important role in slowing and filtering stormwater runoff, resulting in increasing NPS pollution from urban and suburban areas (Chesapeake Bay Foundation 2004). Therefore, it is important to further explore how urban and suburban areas can negatively impact water quality.

Nutrient and sediment runoff from agricultural and urban landscapes contribute to watershed impairment via adverse consequences to the biological and physical environment. Excessive N and P loading can cause eutrophication of surface water bodies (Baird *et al.* 2000). The physical environment also changes with excessive nutrient and sediment loads, affecting hydrology and water chemistry, leading to overall decreases in water quality (Basnyat *et al*. 1999). In addition to the negative impacts of NPS pollution on aquatic ecosystems, it can also jeopardize human health (Osmond and Hardy 2004).

Urban landscapes are a complex matrix of different land cover types including impervious surfaces, lawns, open fields, bare soils and urban forest fragments of varied structure. Land cover type influences the ability of soils to allow infiltration of precipitation versus contributing to runoff. Nutrient loading to surface waters from urban and suburban landscapes is highly variable due to many factors including soil type, vegetation cover, and management practices (Petrovic 1990). In order to better understand NPS pollution in urban areas, it is necessary to study the different land use components found in urban areas, especially turfgrass.

Turfgrass and its propensity to allow runoff and infiltration have been studied in some detail, particularly in golf course applications. Petrovic (1990) reported that in multiple turfgrass studies, little runoff occurred from natural precipitation, indicating soils with this vegetation have a high infiltration capacity. The lack of excessive nutrient loss from turf grass has made it appealing as a buffer strip material to filter out excessive nutrients in runoff. The dense growth habit of turfgrass and the production of thatch, create a tortuous pathway that slows runoff water, reduces sediment loss, and increases infiltration (Linde *et al*. 1995, 1998).

Little research has addressed the use of alternatives to turfgrass that may have less impact, requiring less maintenance and resource input, while at the same time reducing the potential for NPS pollution. Ongoing research in Florida has compared runoff and leaching of N, P, and K from St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] with that from a mixed species landscape (trees, shrubs, and herbaceous perennials; Erickson *et al*. 1999, 2001, 2005). Data on N leaching from these plots indicated that turfgrass was significantly more effective in reducing the amount of N lost through leaching (Erickson *et al*. 1999, 2001). Investigation of P and K leaching showed results similar to N leaching, with turfgrass more effectively reducing nutrient loss (Erickson *et al*. 2005).

While the results of Erickson *et al*. (1999, 2001, 2005) support turfgrass as most effective in reducing nutrient loss from urban and suburban landscapes, additional research investigating alternative landscapes is necessary to fully determine their effectiveness in reducing NPS pollution potential. Research addressing the influence of land cover types in urban landscapes on nutrient and sediment runoff requires controlled experimental designs. An innovative design that utilizes alternative landscape land covers in combination with manipulated precipitation volume was used to quantify impacts of precipitation on runoff, sediment erosion, and transport of nutrients from landscapes. Specifically, land covers of bare soil, mulch, turfgrass, and urban forest were compared. The results of this research will improve designs and BMPs, thereby reducing environmental impacts of urban and suburban landscapes.

Materials and Methods

Research plots were established using a modified split-plot design in May 2004 on a N/NE facing hillside with a 15% slope at Kentland Farm (37.19^{o}N, 80.58^{o}W), near Blacksburg, VA. Precipitation treatments were provided with a triplicate plot design (Figure 2.1) by constructing three adjacent 2.4 m x 2.4 m (8 ft. x 8 ft.) subplots along the slope of the hillside. Each triplicate plot received the same landscape treatments (described below). A total of twelve triplicate plots were located in one row across the hillside with 2.4 m of turfgrass between each plot (Figure 2.2). The plots were constructed without borders.

Eight, 15.2 cm (6 in.) d. PVC pipes cut length-wise in half to form troughs were spaced evenly above each middle plot to collect approximately 50% of precipitation falling on that plot, allowing it to drain and run-on as concentrated flow approximately 0.46 m below the top edge of the lower plot. The troughs were elevated 15 cm above the ground using bent steel wire to reduce impedance of evapotranspiration and interference with growing vegetation. The use of these troughs created three manipulations of precipitation across the triplicate plot, with 100% of ambient precipitation falling in the upper plot, approximately 50% falling in the middle plot, and approximately 150% falling in the lower plot.

Landscape treatments were bare soil, turfgrass, shredded wood mulch, and simulated urban forest. Each landscape treatment was randomly assigned to one triplicate plot within each of three blocks (Figure 2.2a). Turfgrass treatments made use of existing turfgrass (established tall fescue blend), while all other plots received an initial application of Roundup® to kill existing vegetation. Dead vegetation was removed mechanically from the surfaces of non-turfgrass plots using a string trimmer and leaf rake. Root and other below ground vegetation was left intact. The soil was not tilled or otherwise disturbed in any plots except to plant trees in the urban forest plots. Mulched plots received a 7.6 cm thick layer of shredded wood mulch. Each 8 x 8 simulated urban forest subplot was planted with four, 15 gallon containerized, 3.2 cm d. pin oak (*Quercus palustris*) trees and covered with a 7.6 cm thick layer of composted leaf mulch to simulate a forest litter layer (Figure 2.3). Turfgrass within the turfgrass plots and surrounding all of the plots was maintained at a height of approximately 8 cm with a rotary mower. Weeding of non-turfgrass plots by hand was conducted for the duration of the experiment. In addition, a second application of Roundup® was applied to all non-turfgrass plots in late July.

Runoff from each 8 x 8 subplot was collected along the bottom end of the plot by a 15.2 cm (6 in.) d. PVC trough (described above) sunken just below grade, with each end capped. A 7.6 cm wide strip of metal flashing inserted just below the soil surface along the bottom of each plot and lapped over the edge of the trough directed runoff into the trough. Each trough was sloped slightly to drain runoff to one end cap, which was drilled to allow runoff to drain out into collection reservoirs. Collection reservoirs for each 8 x 8 subplot were constructed by sinking a 121 L (32 gallon) garbage can into the ground. A 19 L (5 gallon) bucket was placed inside each can to collect runoff and to allow easy removal for analysis following a rain event. When runoff volumes exceeded the capacity of the 19 L buckets, additional runoff overflowed into the collection reservoirs. Excess water and sediment was removed for measurement and sampling in additional 19 L buckets.

Runoff collected from each plot for 10 rain events between July and December 2004 was filtered at 63 μm to collect sediment using standard brass sieves. Sediment collected was rinsed onto pre-weighed filter paper, allowed to drain, and dried in an oven at 70°C for 2 days. Filter papers were weighed again and sediment mass determined. Water runoff volume was calculated from the mass of water collected in each reservoir by using a digital hanging scale. A weather station located approximately 150 m from the site monitored weather conditions. Rainfall amounts were measured in 0.1 mm increments by a tipping bucket rain gauge. Weather data were recorded on an hourly basis for the first six rain events. The weather station was reprogrammed to record weather data each minute for the remaining four rain events.

Samples of runoff water from three rain events in November and December were drawn from bulk volumes collected and analyzed for concentrations of nitrates and orthophosphates. Nutrient analysis was performed using a Hach DR/2400 spectrophotometer. Nitrate concentrations were measured using Hach method 8039, a high range cadmium reduction method. Orthophosphate concentrations were measured using Hach method 8048, an ascorbic acid method (Hach Company 2002). Total nitrate and phosphate loads were calculated by multiplying nutrient concentrations by the total bulk volume of runoff water from each reservoir.

Statistical analysis of runoff, sediment, and nutrient data was performed using JMP 4.0.4 (SAS Institute 2001). Due to potentially confounding factors between the three subplots in each replicated treatment, results were not analyzed using a split-plot model. Rather, each precipitation manipulation treatment was analyzed as a different experiment across the landscape treatments. At each precipitation manipulation level, a full factorial, mixed model ANOVA design with landscape cover as a fixed effect and precipitation as a random effect tested for significant differences in runoff and eroded sediment between landscape treatments with all rain events compiled. Additionally, proportional runoff and soil erosion across all rain events was characterized by calculating the proportion of precipitation that ran off from each plot, the ratio of sediment mass per precipitation volume, and the sediment mass per runoff volume from each plot. These data were illustrated graphically but were not statistically analyzed. Each rain event was also analyzed separately using one-way ANOVAs with land cover as a fixed effect for differences in runoff volume and eroded sediment mass. Separated means on each date were calculated using Tukey-Kramer honestly significant difference (HSD) comparisons with $\alpha = 0.05$.

Data on nitrate and phosphate concentrations in runoff water was analyzed with two-way ANOVAs using land cover and rain event as fixed effects. Estimates of nitrate and phosphate loads lost from plots were calculated by multiplying nutrient concentrations in subsamples by the total volume of runoff. Because the subsamples were from the bulk of the total runoff collected these should be reliable estimates of total nutrients lost. These data were analyzed with the same ANOVA model. Separated means were calculated for these nutrient measures by rain event, precipitation manipulation, and land cover using Tukey-Kramer honestly significant difference (HSD) comparisons with $\alpha = 0.05$.

Results

The majority of the rain events were of light to moderate intensity and of short duration, common throughout the majority of the year in southwest Virginia, ranging in amounts from 6.9 to 23.9 mm. In comparison, the September 11 rain event was of longer duration (34 hr.) and produced a much greater total depth of rainfall (55.9 mm), resulting from the remnants of Hurricane Frances. Despite differences in the volume of rainfall occurring from event to event, the average intensity of rainfall events was similar across the majority of events, generally ranging from 1.1 to 2.4 mm/hr. (Table 2.1).

More frequent weather data collection for the last four events (Sep 11, Nov 5, Dec 1, Dec 8) allowed for more detailed characterization of these events. Plots of rainfall intensity across each event indicated an advance storm pattern during the Dec. 1 and Dec. 8 rain events, with the majority of precipitation occurring early, while the majority of the Sep. 11 event was delayed until the middle, producing an intermediate storm pattern (Figure 2.4). Spikes in rainfall intensity in the Nov. 5 event were more evenly distributed across the length of the event, making for a more uniform storm pattern. The more detailed characterization of storm events also revealed that the September 11 event was not only of longer duration and greater total precipitation volume, but also had more than double the peak rainfall intensity of other storms (23 mm/hr compared to 6-10 mm/hr, Figure 2.4).

<u>Stormwater runoff</u>

Stormwater runoff volumes measured over the course of the ten rain events varied between land cover treatments and rain events. In all three precipitation manipulation experiments there was a highly significant effect of precipitation volume in a rain event (Table 2.2). In general, the greater the precipitation volume, the greater the volume of runoff. In all three precipitation manipulation experiments there was a significant effect of land cover treatment on runoff (Table 2.2). Overall, and in each of the precipitation manipulation experiments, turfgrass plots contributed the least to runoff volume (means, Table 2.3). In two out of three precipitation manipulation experiments there was a significant interaction between land cover treatment and precipitation volume (Table 2.2) in which at higher precipitation volumes, the difference in runoff contributed by the land cover treatments increased. Turfgrass plots exhibited little change in runoff, whereas other land cover treatments had increased runoff with increased precipitation (Figure 2.5). In another exploration of the relationship between runoff and land cover treatment across all ten events, the proportion of the runoff volume relative to the precipitation volume was calculated. In general, in higher precipitation manipulation experiments, the amount of runoff relative to the precipitation applied decreased (Figure 2.6). Figure 2.6 also shows mulch to generally have a greater rate of runoff, especially at the 50% manipulation treatment, while turfgrass treatments produced the least runoff.

Results from one-way ANOVAs of each individual rain event at each precipitation manipulation level indicate significant differences in runoff volume between land cover treatments in 18 out of 30 date/experiment combinations (Table 2.3). Mean runoff volumes from the turfgrass plots were significantly less than all other plots in two instances (Jul 23, 50% experiment; Aug 6, 50% experiment). Mulched beds contributed significantly more runoff than all other land covers in 6 instances (Aug 2, 50% and 150% experiments; Aug 6, 50% and 150% experiments; Sep 11, 50% experiment; Nov 5, 50%

experiment). In no instance did bare soil plots contribute significantly more runoff volume than all other plots.

Sediment

Sediment losses in runoff varied with land cover treatment in two experiments (100% and 150% experiments, Table 2.4) and with precipitation volume in one experiment (150%, Table 2.4). There were no interactions between land cover and precipitation volume on sediment loss in any experiment. In general, sediment loss was greater with increasing precipitation volumes and turfgrass plots produced the least sediment loss in each precipitation manipulation experiment (means, Table 2.5). When each storm event and precipitation manipulation experiment was analyzed separately with one-way ANOVA, turfgrass plots contributed significantly less sediment than all other plots on two occasions (Jul 23, 50%; Aug 6, 50%), and mulch beds contributed significantly more sediment than all other treatments on six occasions (Aug 2, 50%, 150%; Aug 6, 50%, 150%; Sep 11, 50%; Nov 5, 50%). Urban forest plots contributed the most sediment on seven occasions, but never significantly more than all other plots. Bare soil plots contributed the most sediment on two occasions; neither occasion was significantly different than all other occasions.

In an illustration of the influence of land cover on sediment loss across all rain events, the proportion of the sediment mass lost relative to the precipitation volume applied is presented in Figure 2.7. Here again turfgrass plots tended to allow less sediment erosion and urban forest plots tended to produce greater sediment loss, but losses were more highly variable (Figure 2.7). The propensity of soil to erode, given the volume of runoff, was measured by concentrations of sediment in runoff (ratio of sediment mass to the runoff volume from individual plots). Turfgrass runoff had lower concentrations of sediment, while urban forest plots produced runoff with greater and more varied concentrations of sediment (Figure 2.8).

Nitrate

Land cover treatments influenced the concentration of nitrate in runoff water in only the 150% precipitation experiment on the Dec 1 and Dec 8 rain events. Turfgrass treatments produced lower nitrate levels than other land covers and higher concentrations were found in urban forest plots (Table 2.6). In general, nitrate concentrations were lower at higher precipitation manipulation treatment levels. There were no significant interactions on nitrate concentration in runoff between rain event and land cover at any precipitation manipulation. Significant effects of rain event and land cover on total nitrate lost in runoff were found in the 100% and 150% precipitation experiments (Table 2.7 b, c). Nitrate load differed significantly with land cover in all 3 precipitation experiments (Table 2.7), and in this measure as well, turfgrass plots had the lowest nitrate load in runoff (Table 2.8).

Orthophosphate

Concentrations of orthophosphates in runoff water varied significantly by land cover treatment, and rain event (Table 2.9). Mulched plots generally produced the lowest concentrations of orthophosphates. The highest concentrations of orthophosphates were found in runoff from urban forest plots. At higher precipitation manipulation treatment levels, orthophosphate concentrations tended to be lower compared to concentrations at lower manipulation levels (Table 2.10). Orthophosphate load in runoff also differed by rain event and land cover (Table 2.9), with urban forest plots losing the most, and turfgrass and mulched plots losing the least orthophosphate in runoff (Table 2.11).

Discussion

Results of stormwater runoff and sediment loss measurements suggested that, of the four land covers tested, turfgrass was the most effective treatment for reducing the volume of runoff as well as the amount of sediment carried in the runoff. This finding agrees with previous observations of runoff from turfgrass, which have indicated there is generally little runoff from turfgrass surfaces compared to other land covers under natural precipitation (Petrovic 1990, Erickson *et al*. 1999, 2001). This low rate of runoff is the result of a high infiltration capacity, which can be attributed to the dense growth habit of turfgrass and its ability to produce thatch. This results in a tortuous pathway that slows runoff, allowing more time for infiltration (Petrovic 1990, Linde *et al*. 1995, 1998).

In contrast to turfgrass, mulched plots tended to produce the greatest volumes of stormwater runoff, while urban forest plots produced the second highest levels of runoff. Some crusting of mulch surfaces may have reduced the ability for water to infiltrate these surfaces. However, it is more likely that these results were observed due to higher antecedent moisture conditions in these plots. The mulch layer contained in these plots would have served to reduce the rate of evaporation of water from the soil surface. Likewise, this would explain the lower levels of runoff that were collected from bare soil plots. The soil contained in these plots was directly exposed to sunlight and heat that promoted drying of the soil, leading to lower antecedent soil moisture levels. As a result, greater volumes of water were able to infiltrate into bare soil plots rather than runoff. Some other important implications of antecedent soil moisture are discussed later.

Despite having the greatest volume of runoff of the four land covers tested, the mulched plots generally did not loose as much sediment as did bare soil and urban forest plots. This suggests the wood mulch layer was effective in holding the soil in place underneath. Because the mulch acted as a barrier to the soil, the mulch was able to absorb the force of impact of raindrops that would have dislodged soil particles on the surface of the bare soil plots (Schwab *et al*. 1996).

Surprisingly, urban forest plots produced the greatest sediment losses in runoff water. This was most likely due to the amount of disturbance to these plots during construction, which involved loosening a majority of the soil in each plot. In addition, the trees planted in these urban forest plots were not fully established, having only been planted two months prior to the first rain event for which data were collected. Had these plots been fully established, it is likely that runoff and sediment loss would have been lower. In a buffer strip study comparing a switchgrass (*Panicum virgatum* L. cv. Cave-n-Rock) buffer with a combination buffer of switchgrass followed by a multispecies riparian area, Lee *et al*. (2000) found that a deep-rooted woody plant buffer provided a high infiltration capacity, capable of trapping clay and soluble nutrients in runoff not trapped in the switchgrass. In comparison, when woody plants are not as densely planted, turfgrass may work equally as well or outperform a mix of turfgrass and established trees and shrubs. A study of vegetative buffer strips found that established young trees and shrubs located in the lower half of grass buffer strips had no effect on the performance of the buffer strip in reducing sediment and nutrient losses compared to grass only buffer strips (Schmitt *et al*. 1999).

The two nutrients most cited as contributing to non-point source pollution in surface waters are nitrogen and phosphorus. While there are many forms of these elements influencing water quality, this study focused on collecting information on the loss of nitrate and orthophosphate in runoff from these plots in a subset of the rain events. In general, nitrate concentrations in runoff were relatively low, not exceeding 1.25 mg/L

(Table 2.6). Nitrate concentrations in runoff from turfgrass plots were lower, in the range of 0.33 to 0.77 mg/L. Previous studies of nitrate in runoff from turfgrass reported similar results, even with fertilizer applications. Shuman (2002) found nitrate concentrations in runoff from fertilized "Tifway" bermudagrass [*Cynodon dactylon* (L.) Pers.] to be around 0.5 mg/L with peak measurements of 1-1.5 mg/L. Nitrate loss from sloped plots of creeping bentgrass (*Agrostis palustris* Huds.) and perennial ryegrass (*Lolium perenne* L.) rarely produced runoff with nitrate concentrations exceeding 1 mg/L (Linde and Watschke 1997).

Nitrogen contributions to urban stormwater runoff and surface waters are probably not as great as has been measured in agricultural areas (Coulter *et al*. 2004). For example, the majority of N fertilizer applied to turfgrass is usually taken up by the turfgrass plants or is lost to leaching through the soil (Petrovic 1990). Morton *et al*. (1988) reported greater than 93% of inorganic-N lost from study plots was lost through leaching. Leaching losses of N would more likely contribute to reduced groundwater quality, but could still indirectly impair surface waters as well. There are likely to be important vegetation influences on nitrate leaching through the soil profile. Research comparing leaching of N from a turfgrass lawn and an alternative landscape consisting of a variety of woody and herbaceous perennials found significantly greater N leaching from the alternative landscape, suggesting turfgrass is more effective at rapidly absorbing nutrients (Erickson *et al*. 2001). Petrovic (1990) suggests that N losses through leaching can be reduced by implementing proper landscape management practices.

Concentrations of orthophosphates in runoff water (Table 2.10) tended to be higher than those of nitrates (Table 2.6). Concentrations measured in the bare soil, turfgrass, and mulched treatments were similar to the 0.5 to 1 mg/L range of concentrations that were measured in runoff from unfertilized turfgrass plots in another study (Shuman 2002). Concentrations measured in the urban forest plots were surprisingly higher, ranging as high as 3.42 mg/L (Table 2.10). This was likely a result of residual P fertilizer that was in the growing media of the containerized pin oak trees planted in the urban forest plots. In addition, the higher concentrations of orthophosphates may be linked to the greater losses of sediment that were measured in the urban forest plots. Orthophosphates often attach to soil particles, thus, P loss is often correlated with sediment loss. The correlation between orthophosphate lost and sediment eroded across the rain events in this study was not high, however, only the orthophosphate dissolved in runoff water was analyzed. It is likely a lot of this phosphorus was missed by not analyzing nutrients in eroded sediment. Phosphorus laden runoff has been implicated as a potentially stronger determinant of surface water quality than nitrogen.

There were a number of factors that limited the quantity and quality of conclusions that can be drawn from this study. For example, the plot size used in this experiment (2.4 m x 2.4 m) was smaller than is typically used in runoff studies (e.g. Schmitt *et al*. 1999, Lee *et al*. 2000). The smaller plots likely kept runoff velocity low, reducing opportunities to create rill or gully erosion. This situation may have masked some important differences in the influence of land cover on runoff volume or sediment mass eroded. However, this study was a model of urban spaces. Smaller plot sizes mimicked small areas of turf or mulched beds that one would commonly find in urban areas, and differences in these measures attributable to land cover were discernable.

Another limitation of the experimental design was the lack of plot borders. Impermeable borders between the triplicate plots and adjacent untreated land would reduce the incidence of stormwater run-on into the plots, and insure that runoff from the plots was not lost to adjacent land. However, because of the position of these plots in relation to the slope of the research site, run-on and runoff via the top or sides of plots was probably minimal. Also, the probability of confounding influences of run-on would be greatest between subplots which were aligned with the slope. Because the statistical analysis treated each sub-plot (precipitation manipulation) as a separate experiment the introduced error within any one experiment is likely to be small.

The precipitation manipulation treatments were designed to provide three different precipitation volumes, and three different precipitation rates, within any one rain event. Because of the potential for confounding effects, precipitation manipulations were analyzed as separate experiments. This was a conservative approach to reduce the probability of a Type I error in which differences might have been observed between imposed precipitation rates that did not exist. In the following paragraphs there is discussion of some additional potential sources of error in the initial experimental design that were reduced by analyzing precipitation manipulation in three separate experiments. A caveat is offered, however. Across all precipitations, rain events, and land cover treatments, the relationship between volume of water applied to each plot and the runoff volume collected was strongly positive. This indicates that the design manipulated rainfall in the expected direction, with 50% treatments having smaller volumes of runoff and 150% treatments having larger volumes of runoff than those plots under ambient precipitation.

In addition to the potential for run-on onto the plots that was not controlled for (described earlier), it is probably true that the manipulations did not impose precisely 50%, and 150% of ambient precipitation. All of the rain entering the PVC troughs over the 50% plots may not have drained onto the 150% plots. Some rain could have splashed out, contributing to more than 50% of ambient precipitation to those middle subplots, and less than 150% to the lower plots. More likely, based on personal observation, water tended to stay in the PVC trough until enough water collected to move the water down the trough. This would allow somewhat less than 150% of ambient precipitation to reach the lower plots, but have no influence on the 50% plots.

The influence of evapotranspiration on the antecedent moisture in any of these plots should be large. Antecedent moisture would affect the ability of soils to allow infiltration versus runoff of stormwater, both through influences on soil structure and permeability, and on the amount of stormwater needed to saturate the soil. Soil structure can influence antecedent moisture, but soils were very consistent across the research site. Temperature, humidity, and wind influence evapotransiration, and therefore, antecedent moisture. These were dynamic factors over time, but were the same across all plots, with the possible exception of wind on the 50% plots (see below). The land cover treatments, including influences of plant growth, surely influenced soil moisture dynamics. Measurements of evapotranspiration were not taken and soil moisture changes were not tracked. These were likely covarying factors in the measurements that were collected. A particular unintended factor with the potential to influence all of these variables is the 50% shading and potential wind block that resulted from the 50% trough cover. Although steps were taken to reduce the influence of these troughs by raising them off the ground, soil moisture levels likely remained higher in these plots due to decreased evapotranspiration. Higher antecedent soil moisture levels could have led to greater than expected runoff volumes from 50% plots.

While the 150% precipitation manipulation probably imposed about 150% of ambient precipitation volume to the lower plots, one third of that volume was not applied as precipitation *per se*. Rather it was concentrated flow from the troughs from the plot above. It did not provide the impact velocity of natural precipitation. Raindrop impact acts with a potentially different force to loosen sediment particles from the soil surface in a different manner than does water flowing over the surface. On the other hand, increased concentrated flow could have contributed to rill erosion in the 150% plots. This is a likely confounding factor influencing runoff volume, and especially sediment and nutrient loss from the 150% plots.

Another factor influencing patterns of stormwater runoff is the rain event itself. Many aspects of a rain event, including, but not limited to, duration, average intensity, peak intensity, storm pattern, and precipitation type all have an influence on how runoff, as well as sediment and nutrient loss, will occur. Average intensities for each of the ten rain events were fairly similar, despite wide variations in the rainfall amounts (Table 2.1). Therefore, it is helpful to look at how intensity varies over the duration of a rain event. From plots of intensity measured over the duration of an event, peak intensities as well as storm patterns can be determined. Plots of intensity from the last 4 events show how much greater peak intensities can be compared to average intensities. A more extreme example of this can be seen in the Sep 11 rain event, which had an average intensity of 1.5 mm/hr., but a peak intensity of 23.4 mm/hr. (Figure 2.4). This more intense period during the rain event indicates a heavier volume of rainfall was occurring. Heavier rainfall usually translates into more impact on the soil surface resulting in larger amounts of sediment being dislodged and carried away with runoff water.

Storm patterns can shape how runoff will occur. Advance storm patterns deposit the majority of the precipitation at the beginning of the event, when soils have not yet saturated, allowing for more infiltration and less runoff of precipitation. In contrast, delayed patterns typically produce greater runoff volumes, a result of the soil becoming saturated before the majority of the precipitation occurs more intensely near the end of the rain event (Schwab *et al*. 1993). While there were differences in storm patterns that can be seen in the rainfall intensity plots of the last four events observed in this research (Figure 2.4), it is difficult to discern possible expected differences in the total runoff volumes. Any differences that may have occurred were probably small relative to other factors, particularly differences in antecedent soil moisture levels for each of these four events. Therefore, there was no apparent influence of storm pattern on runoff or erosion.

Conclusions

Urban landscapes are like a land cover puzzle made up of many different kinds of pieces. This research has analyzed some of the pieces and found which ones work better to protect our water quality. The results of this research provide support to prior research that has shown turfgrass to be an effective land cover for the reduction of NPS pollution by reducing runoff water volumes as well as sediment and nutrient losses. In this study, turfgrass was more efficient at reducing runoff water volume and sediment and nitrate loss than other treatments. However, in terms of orthophosphate concentrations, bare soil and mulched plots were comparable to turfgrass.

Unfortunately, few conclusions can be made about the urban forest plots. What can be said about these plots is that they were not fully established and experienced more disturbance than other plots during construction. As a result, measurements of runoff, sediment, and orthophosphate were higher than what would be expected from established plots. Had these plots been established, it is possible that an urban forest land cover may have been as effective as turfgrass. Rather, these plots acted more like newly planted trees (as part of a newly established landscape) and suggest sediment and nutrient loss can be greater in the first year after planting as compared to an established landscape.

The lack of plot borders, along with plot size and the confounding effects of the mechanisms used to create the different precipitation treatments, lead to possible improvements that could be made in this experimental design. The design of this experiment could be simplified and improved by removing the precipitation treatment layer. In turn, the triplicate plots could be turned into single plots with a downhill slope length of 7.6 m, triple the length in the current design. Along with this, borders along the edges of the plots should be installed to eliminate issues of water running on or off the plots. As an alternative to lengthening the plots, the precipitation manipulation treatments could be replaced with other treatments, such as a series of fertilizer treatments.

An additional caveat to this study, research on urban land covers was carried out in an agricultural setting. Thus, the effects of dry deposition due to air pollution and soil compaction are limited. Also, nutrient losses from these plots were likely to have been heavily influenced by any previous fertilizer applications during prior use of the land. Despite the issues and possible error sources in the experimental design, the results do provide useful information. Together with previous knowledge, the results of this research will help improve both design and management practices related to urban and suburban landscapes.

Literature Cited

Baird, J.H., N.T. Basta, R.L. Huhnke, G.V. Johnson, M.E. Payton, D.E. Storm, C.A. Wilson, M.D. Smolen, D.L. Martin, and J.T. Cole. 2000. Best management practices to reduce pesticide and nutrient runoff from turf. p. 268-293. In: J.M. Clark and M.P. Kenna (eds.). Fate and Management of Turfgrass Chemicals. American Chemical Society, Washington, D.C.

Basnyat, P., L.D. Teeter, K.M. Flynn, and B.G. Lockaby. 1999. Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. Environmental Management 23(4): 539-549.

Coulter, C.B., R.K. Kolka, and J.A. Thompson. 2004. Water quality in agricultural, urban, and mixed land use watersheds. Journal of the American Water Resources Association 40(6): 1593-1601.

Chesapeake Bay Foundation. 2004. 2004 State of the Bay Report. Annapolis, MD. Accessed 29 March 2005. http://www.cbf.org/site/DocServer/w33475.pdf?docID=2563

Erickson, J.E., J.L. Cisar, G.H. Snyder, and J.C. Volin. 2005. Phosphorus and potassium leaching under contrasting residential landscape models established on a sandy soil. Crop Science 45: 546-552.

Erickson, J.E., J.L. Cisar, J.C. Volin, and G.H. Snyder. 2001. Comparing nitrogen runoff and leaching between newly established St. Augustinegrass turf and an alternative residential landscape. Crop Science 41: 1889-1895.

Erickson, J.E., J.C. Volin, J.L. Cisar, and G.H. Snyder. 1999. A facility for documenting the effect of urban landscape type on fertilizer nitrogen runoff. Proceedings of the Florida State Horticulture Society 112: 266-269.

Hach Company. 2002. DR/2400 Spectrophotometer Procedure Manual. Loveland, CO: Hach Company.

Lee, K-H., T.M. Isenhart, R.C. Schultz, and S.K. Mickelson. 2000. Multispecies riparian buffers trap sediment and nutrients during rainfall simulations. Journal of Environmental Quality 29: 1200-1205.

Linde, D.T. and T.L Watschke. 1997. Nutrients and sediment in runoff from creeping bentgrass and perennial ryegrass turfs. Journal of Environmental Quality 26: 1248-1254.

Linde, D.T., T.L. Watschke, and A.R. Jarrett. 1998. Surface runoff comparison between creeping bentgrass and perennial ryegrass turf. Journal of Turfgrass Management 2: 11-34.

Linde, D.T., T.L. Watschke, A.R. Jarrett, and J.A. Borger. 1995. Surface runoff assessment from creeping bentgrass and perennial ryegrass turf. Agronomy Journal 87: 176-182.

Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. Journal of Environmental Quality 17: 124-130.

Osmond, D.L. and D.H. Hardy. 2004. Characterization of turf practices in five North Carolina communities. Journal of Environmental Quality 33(2): 656-575.

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. Journal of Environmental Quality 19(1): 1-14.

SAS Institute. 2001. JMP version 4.0.4. Cary, NC: SAS Institute.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation, widths, and contaminants. Journal of Environmental Quality 28: 1479-1489.

Schwab, G.O., D.D. Fangmeier, and W.J. Elliot. 1996. Soil and Water Management Systems. 4th ed. New York: John Wiley and Sons, Inc. 371 p.

Schwab, G.O., D.D. Fangmeier, W.J. Elliot, and R.K. Frevert. 1993. Soil and Water Conservation Engineering. 4th ed. New York: John Wiley and Sons, Inc. 507 p.

Shuman, L.M. 2002. Phosphorus and nitrate in runoff following fertilizer application to turfgrass. Journal of Environmental Quality 31: 1710-1715.

Table 2.1. Summary of ten rainfall events between July and December 2004. Precipitation amounts were measured by an on-site weather station. Average intensity was calculated as total rainfall divided by event duration.

Rainfall event date	Total precipitation (mm)	Average intensity (mm/hr.)
Jul 3	21.8	2.4
Jul 12	12.4	1.8
Jul 19	6.9	2.3
Jul 23	15.5	1.9
Aug 2	23.9	4.1
Aug 6	13.7	1.7
Sep 11	55.9	1.5
Nov 5	19.5	1.6
Dec 1	17.7	1.2
Dec 8	19.1	1.1

Table 2.2. Results of ANOVA tests of runoff volume measured from different land cover treatments and rain events at precipitation manipulations of a) 50%, b) 100%, c) 150%.

a)

50% treatment				
Effect	df	MS	F	
land cover	3	80.9	39.5	***
rain event	1	2421.0	1182.0	***
land cover X rain event	3	68.7	33.5	***
error	112	2.0		

* p<0.05, ** p<0.01, *** p<0.001

b)

100% treatment				
Effect	df	MS	F	
land cover	3	68.9	3.1	*
rain event	1	3757.6	171.1	***
land cover X rain event	3	26.4	1.2	
error	112	22.0		

* p<0.05, ** p<0.01, *** p<0.001

c)

150% treatment				
Effect	df	MS	F	
land cover	3	326.6	49.9	***
rain event	1	7726.9	1181.0	***
land cover X rain event	3	247.1	37.8	***
error	112	6.5		

* p<0.05, ** p<0.01, *** p<0.001

Table 2.3. Mean runoff volumes (L) and standard errors measured from subplots during ten rain events.

Date	Precipitation manipulation	Land cover							
		Bare soil		Mulch		Turfgrass		Urban forest	
Jul 3	50%	6.85b[z]	+/-0.30	9.02a	+/-0.63	6.37b	+/-0.09	7.43ab	+/-0.30
	100%	13.30ab	+/-1.64	10.83ab	+/-1.10	9.00b	+/-0.81	14.07a	+/-0.32
	150%	11.58b	+/-0.82	15.53a	+/-0.55	11.63b	+/-0.44	14.3a	+/-0.17
Jul 12	50%	4.93ab	+/-0.28	5.60a	+/-0.21	4.00b	+/-0.21	4.30b	+/-0.17
	100%	9.37a	+/-2.03	6.17a	+/-0.92	4.55a	+/-3.05	8.03a	+/-0.20
	150%	8.00a	+/-1.25	9.13a	+/-0.20	6.33a	+/-0.33	7.43a	+/-0.50
Jul 19	50%	0.88ab	+/-0.05	0.90a	+/-0.06	0.63b	+/-0.05	0.87ab	+/-0.12
	100%	1.77a	+/-0.38	0.63a	+/-0.33	0.82a	+/-0.41	1.69a	+/-0.03
	150%	1.79a	+/-0.26	1.98a	+/-0.06	1.44a	+/-0.06	1.98a	+/-0.07
Jul 23	50%	6.03b	+/-0.20	7.97a	+/-0.38	4.53c	+/-0.26	6.93ab	+/-5.59
	100%	10.53a	+/-1.68	8.17a	+/-2.24	5.50a	+/-2.02	11.47a	+/-0.52
	150%	9.07a	+/-0.97	12.30a	+/-0.55	8.10a	+/-0.25	8.10a	+/-3.23
Aug 2	50%	5.92b	+/-0.30	10.42a	+/-0.94	4.58b	+/-0.22	5.50b	+/-1.94
	100%	9.67a	+/-1.72	10.25a	+/-3.39	6.83a	+/-1.08	10.92a	+/-0.71
	150%	9.00b	+/-0.87	18.25a	+/-1.95	8.42b	+/-0.36	12.58b	+/-1.12
Aug 6	50%	4.13b	+/-0.23	6.00a	+/-0.15	3.10c	+/-<0.01	4.37b	+/-0.47
	100%	6.77a	+/-0.87	5.47a	+/-2.69	4.67a	+/-0.52	8.03a	+/-0.18
	150%	6.80b	+/-0.65	11.30a	+/-0.79	5.57b	+/-0.30	7.63b	+/-0.27
Sep 11	50%	17.03b	+/-1.14	27.87a	+/-1.79	14.32b	+/-1.01	18.28b	+/-4.61
	100%	23.29a	+/-4.70	28.47a	+/-15.8	20.63a	+/-1.94	25.93a	+/-1.69
	150%	27.86b	+/-2.97	48.99a	+/-4.58	23.57b	+/-1.64	37.07ab	+/-2.66
Nov 5	50%	4.59b	+/-0.49	9.14a	+/-0.55	5.35b	+/-0.15	5.15b	+/-0.39
	100%	7.62a	+/-1.47	7.47a	+/-3.51	7.42a	+/-0.87	9.69a	+/-0.81
	150%	8.12b	+/-1.24	20.38a	+/-3.01	9.38b	+/-0.37	14.42ab	+/-0.37
Dec 1	50%	5.97a	+/-1.50	6.31a	+/-0.34	4.59a	+/-0.11	4.36a	+/-0.36
	100%	6.83a	+/-0.50	5.26a	+/-1.90	6.81a	+/-1.02	9.14a	+/-0.57
	150%	7.72b	+/-0.28	12.11a	+/-1.18	8.24b	+/-0.14	10.41ab	+/-0.20
Dec 8	50%	4.44b	+/-0.21	7.72a	+/-0.79	6.16ab	+/-1.00	5.53ab	+/-0.54
	100%	7.31a	+/-0.13	6.86a	+/-2.78	8.10a	+/-0.65	10.21a	+/-0.53
	150%	9.04b	+/-0.53	14.78a	+/-1.69	9.32b	+/-0.27	12.21ab	+/-0.31
Mean	50%	6.08	+/-1.32	9.10	+/-2.25	5.36	+/-1.12	6.27	+/-1.45
	100%	9.65	+/-1.79	8.96	+/-2.35	7.43	+/-1.64	10.92	+/-1.95
	150%	9.90	+/-2.15	16.48	+/-3.95	9.20	+/-1.82	12.61	+/-2.97

[z]Means separation in rows by Tukey-Kramer HSD test, α = 0.05 (n=3). Treatments within rows with the same letters are not significantly different.

Table 2.4. Results of ANOVA tests of sediment mass measured from different land cover treatments and rain events at precipitation manipulations of a) 50%, b) 100%, c) 150%.

a)

50% treatment				
Effect	df	MS	F	
land cover	3	0.18	1.44	
rain event	1	0.05	0.44	
land cover X rain event	3	0.20	1.60	
error	112	0.13		

* p<0.05, ** p<0.01, *** p<0.001

b)

100% treatment				
Effect	df	MS	F	
land cover	3	2.26	4.60	**
rain event	1	<0.01	<0.01	
land cover X rain event	3	0.04	0.08	
error	112	0.49		

* p<0.05, ** p<0.01, *** p<0.001

c)

150% treatment				
Effect	df	MS	F	
land cover	3	2.04	4.86	**
rain event	1	5.15	12.25	***
land cover X rain event	3	0.51	1.21	
error	112	0.42		

* p<0.05, ** p<0.01, *** p<0.001

Table 2.5. Mean sediment masses (g) and standard errors measured in runoff water from subplots during ten rain events.

Date	Precipitation manipulation	Land cover							
		Bare soil		Mulch		Turfgrass		Urban forest	
Jul 3	50%	6.85b[z]	+/-0.30	9.02a	+/-0.63	6.37b	+/-0.09	7.43ab	+/-0.30
	100%	13.30ab	+/-1.64	10.83ab	+/-1.10	9.00b	+/-0.81	14.07a	+/-0.32
	150%	11.58b	+/-0.82	15.53a	+/-0.55	11.63b	+/-0.44	14.3a	+/-0.17
Jul 12	50%	4.93ab	+/-0.28	5.60a	+/-0.21	4.00b	+/-0.21	4.30b	+/-0.17
	100%	9.37a	+/-2.03	6.17a	+/-0.92	4.55a	+/-3.05	8.03a	+/-0.20
	150%	8.00a	+/-1.25	9.13a	+/-0.20	6.33a	+/-0.33	7.43a	+/-0.50
Jul 19	50%	0.88ab	+/-0.05	0.90a	+/-0.06	0.63b	+/-0.05	0.87ab	+/-0.12
	100%	1.77a	+/-0.38	0.63a	+/-0.33	0.82a	+/-0.41	1.69a	+/-0.03
	150%	1.79a	+/-0.26	1.98a	+/-0.06	1.44a	+/-0.06	1.98a	+/-0.07
Jul 23	50%	6.03b	+/-0.20	7.97a	+/-0.38	4.53c	+/-0.26	6.93ab	+/-5.59
	100%	10.53a	+/-1.68	8.17a	+/-2.24	5.50a	+/-2.02	11.47a	+/-0.52
	150%	9.07a	+/-0.97	12.30a	+/-0.55	8.10a	+/-0.25	8.10a	+/-3.23
Aug 2	50%	5.92b	+/-0.30	10.42a	+/-0.94	4.58b	+/-0.22	5.50b	+/-1.94
	100%	9.67a	+/-1.72	10.25a	+/-3.39	6.83a	+/-1.08	10.92a	+/-0.71
	150%	9.00b	+/-0.87	18.25a	+/-1.95	8.42b	+/-0.36	12.58b	+/-1.12
Aug 6	50%	4.13b	+/-0.23	6.00a	+/-0.15	3.10c	+/-<0.01	4.37b	+/-0.47
	100%	6.77a	+/-0.87	5.47a	+/-2.69	4.67a	+/-0.52	8.03a	+/-0.18
	150%	6.80b	+/-0.65	11.30a	+/-0.79	5.57b	+/-0.30	7.63b	+/-0.27
Sep 11	50%	17.03b	+/-1.14	27.87a	+/-1.79	14.32b	+/-1.01	18.28b	+/-4.61
	100%	23.29a	+/-4.70	28.47a	+/-15.8	20.63a	+/-1.94	25.93a	+/-1.69
	150%	27.86b	+/-2.97	48.99a	+/-4.58	23.57b	+/-1.64	37.07ab	+/-2.66
Nov 5	50%	4.59b	+/-0.49	9.14a	+/-0.55	5.35b	+/-0.15	5.15b	+/-0.39
	100%	7.62b	+/-1.47	7.47a	+/-3.51	7.42b	+/-0.87	9.69b	+/-0.81
	150%	8.12b	+/-1.24	20.38a	+/-3.01	9.38b	+/-0.37	14.42ab	+/-0.37
Dec 1	50%	5.97a	+/-1.50	6.31a	+/-0.34	4.59a	+/-0.11	4.36a	+/-0.36
	100%	6.83a	+/-0.50	5.26a	+/-1.90	6.81a	+/-1.02	9.14a	+/-0.57
	150%	7.72b	+/-0.28	12.11a	+/-1.18	8.24b	+/-0.14	10.41ab	+/-0.20
Dec 8	50%	4.44b	+/-0.21	7.72a	+/-0.79	6.16ab	+/-1.00	5.53ab	+/-0.54
	100%	7.31a	+/-0.13	6.86a	+/-2.78	8.10a	+/-0.65	10.21a	+/-0.53
	150%	9.04b	+/-0.53	14.78a	+/-1.69	9.32b	+/-0.27	12.21ab	+/-0.31
Mean	50%	6.08	+/-1.32	9.10	+/-2.25	5.36	+/-1.12	6.27	+/-1.45
	100%	9.65	+/-1.79	8.96	+/-2.35	7.43	+/-1.64	10.92	+/-1.95
	150%	9.90	+/-2.15	16.48	+/-3.95	9.20	+/-1.82	12.61	+/-2.97

[z]Means separation in rows by Tukey-Kramer HSD test, $\alpha = 0.05$ (n=3). Treatments within rows with the same letters are not significantly different.

Table 2.6. Mean nitrate concentrations (mg/L) and standard errors measured in runoff water from subplots during three rain events.

Date	Precipitation manipulation	Land cover							
		Bare soil		Mulch		Turfgrass		Urban forest	
Nov 5	50%	0.97a[z]	+/-0.12	2.03a	+/-0.80	0.60a	+/-0.06	2.77a	+/-1.72
	100%	0.60a	+/-0.06	1.23a	+/-0.28	0.60a	+/-0.06	2.33a	+/-1.18
	150%	0.57a	+/-0.09	1.07a	+/-0.12	0.73a	+/-0.20	0.90a	+/-0.17
Dec 1	50%	1.10a	+/-0.21	0.80a	+/-0.38	0.77a	+/-0.12	1.07a	+/-0.30
	100%	0.90a	+/-0.20	1.00a	+/-0.15	0.53a	+/-0.03	0.90a	+/-0.17
	150%	0.70ab	+/-0.06	0.77ab	+/-0.12	0.67a	+/-0.03	1.07b	+/-0.07
Dec 8	50%	1.00a	+/-0.15	1.13a	+/-0.26	0.47a	+/-0.12	0.93a	+/-0.15
	100%	0.83a	+/-0.29	0.63a	+/-0.07	0.33a	+/-0.03	0.77a	+/-0.18
	150%	0.47a	+/-0.07	0.70ab	+/-0.15	0.43a	+/-0.03	0.97b	+/-0.03

[z]Means separation in rows by Tukey-Kramer HSD test, $\alpha = 0.05$ (n=3). Treatments within rows with the same letters are not significantly different.

Table 2.7. Results of ANOVA tests of nitrate concentrations and nitrate load lost in runoff from different land cover treatments and rain events at precipitation manipulations of a) 50%, b) 100%, c) 150%.

a)

50% Treatment					
		NO_3 concentration		NO_3 load	
Effect	df	F	P	F	p
land cover	3	2.93	0.054	4.24	0.015
rain event	2	1.75	0.195	2.23	0.129
land cover X rain event	6	1.165	0.357	1.56	0.2
error	24	MSE = 0.304		MSE = 0 .335	

b)

100% Treatment					
		NO_3 concentration		NO_3 load	
Effect	df	F	p	F	p
Land cover	3	6.97	0.0016	7	0.0015
rain event	2	4.61	0.0203	2.86	0.0769
Land cover X rain event	6	1.5	0.218	0.72	0.639
Error	24	MSE = 0.156		MSE = 0.260	

c)

150% Treatment					
		NO_3 concentration		NO_3 load	
Effect	df	F	p	F	p
Land cover	3	9.56	0.0002	21.75	<0.0001
rain event	2	4.14	0.0285	3.26	0.0561
Land cover X rain event	6	1.27	0.308	1.55	0.204
Error	24	MSE = 0.066		MSE = 0.113	

Table 2.8. Mean nitrate load (mg) and standard errors measured in runoff water from subplots during three rain events.

Date	Precipitation manipulation	Land cover							
		Bare soil		Mulch		Turfgrass		Urban forest	
Nov 5	50%	4.43ab[z]	+/-0.68	18.7a	+/-7.29	3.23b	+/-0.4	12.9ab	+/-7.11
	100%	4.81a	+/-0.38	8.47a	+/-3.24	4.54a	+/-0.89	22.1a	+/-10.83
	150%	4.71a	+/-1.13	22.3b	+/-5.33	6.74a	+/-1.62	13.0ab	+/-1.60
Dec 1	50%	6.73a	+/-2.22	5.27a	+/-2.74	3.50a	+/-0.51	4.78a	+/-1.51
	100%	5.95a	+/-1.02	4.90a	+/-1.54	3.68a	+/-0.74	8.03a	+/-1.07
	150%	5.37ab	+/-0.29	9.27ab	+/-1.54	5.49a	+/-0.24	11.1b	+/-0.91
Dec 8	50%	4.40ab	+/-0.56	9.11a	+/-2.98	2.74b	+/-0.55	5.13ab	+/-0.87
	100%	6.11a	+/-2.17	4.39a	+/-2.04	2.69a	+/-0.31	7.76a	+/-1.60
	150%	4.29a	+/-0.88	10.8ab	+/-3.10	4.04a	+/-0.34	11.8b	+/-0.14

Means separation in rows by Tukey-Kramer HSD test, $\alpha = 0.05$ (n=3). Treatments within rows with the same letters are not significantly different.

Table 2.9. Results of ANOVA tests of phosphate concentrations and phosphate load lost in runoff from different land cover treatments and rain events at precipitation manipulations of a) 50%, b) 100%, c) 150%.

a)

50% Treatment					
		PO_4 concentration		PO_4 load	
Effect	df	F	p	F	p
Land cover	3	7.6	0.001	2.55	0.0792
rain event	2	7.64	0.0027	6.82	0.0045
Land cover X rain event	6	0.56	0.755	0.87	0.53
Error	24	MSE = 0.232		MSE = 0 .323	

b)

100% Treatment					
		PO_4 concentration		PO_4 load	
Effect	df	F	p	F	p
Land cover	3	5.33	0.0059	16.99	<0.0001
rain event	2	15.65	<0.0001	24.11	<0.0001
Land cover X rain event	6	0.37	0.894	0.73	0.631
Error	24	MSE = 0.214		MSE = 0.170	

c)

150% Treatment					
		PO_4 concentration		PO_4 load	
Effect	df	F	p	F	p
Land cover	3	8.37	0.0006	12.33	<0.0001
rain event	2	37.02	<0.0001	43.13	<0.0001
Land cover X rain event	6	1.33	0.28	1.32	0.29
Error	24	MSE = 0.143		MSE = 0.165	

Table 2.10. Mean orthophosphate concentrations (mg/L) and standard errors measured in runoff water from subplots during three rain events.

Date	Precipitation manipulation	Land cover							
		Bare soil		Mulch		Turfgrass		Urban forest	
Nov 5	50%	1.44ab[z]	+/-0.18	1.32a	+/-0.26	1.84ab	+/-0.40	3.42b	+/-0.71
	100%	1.16a	+/-0.13	1.65ab	+/-0.41	1.27ab	+/-0.19	2.58b	+/-0.38
	150%	1.12a	+/-0.16	1.09a	+/-0.29	1.72a	+/-0.59	1.71a	+/-0.25
Dec 1	50%	1.31a	+/-0.57	0.58a	+/-0.24	0.68a	+/-0.13	1.97a	+/-0.69
	100%	0.46a	+/-0.09	0.47a	+/-0.20	0.80a	+/-0.34	1.05a	+/-0.19
	150%	0.40ab	+/-0.06	0.27a	+/-0.07	0.35ab	+/-0.09	0.76b	+/-0.02
Dec 8	50%	1.35a	+/-0.53	0.59a	+/-0.13	0.96a	+/-0.19	1.48a	+/-0.29
	100%	0.57a	+/-0.12	0.55a	+/-0.18	0.71a	+/-0.19	1.13a	+/-0.45
	150%	0.42ab	+/-0.05	0.39ab	+/-0.10	0.30a	+/-0.09	0.86b	+/-0.05

[z]Means separation in rows by Tukey-Kramer HSD test, $\alpha = 0.05$ (n=3). Treatments within rows with the same letters are not significantly different.

Table 2.11. Mean orthophosphate load (mg) and standard errors measured in runoff water from subplots during three rain events.

Date	Precipitation manipulation	Land cover							
		Bare soil		Mulch		Turfgrass		Urban forest	
Nov 5	50%	6.70a[z]	+/-1.23	12.35a	+/-2.98	9.71a	+/-1.89	17.05a	+/-2.14
	100%	9.33a	+/-0.88	10.13a	+/-2.52	9.33a	+/-1.70	25.03b	+/-2.88
	150%	9.51a	+/-2.84	22.91a	+/-8.38	16.26a	+/-5.88	24.84a	+/-4.09
Dec 1	50%	9.58a	+/-6.24	3.65a	+/-1.46	3.14a	+/-0.63	8.33a	+/-2.53
	100%	3.07ab	+/-0.42	1.84a	+/-0.22	5.82ab	+/-3.12	9.73b	+/-2.30
	150%	3.10a	+/-0.40	3.13a	+/-0.67	2.90a	+/-0.77	7.94b	+/-0.09
Dec 8	50%	5.82a	+/-2.07	4.76a	+/-1.57	5.98a	+/-1.51	8.40a	+/-2.26
	100%	4.17ab	+/-0.88	2.81a	+/-0.33	5.79ab	+/-1.65	11.32b	+/-2.36
	150%	3.76a	+/-0.43	5.71ab	+/-1.60	2.75a	+/-0.81	10.57b	+/-0.81

[z]Means separation in rows by Tukey-Kramer HSD test, $\alpha = 0.05$ (n=3). Treatments within rows with the same letters are not significantly different.

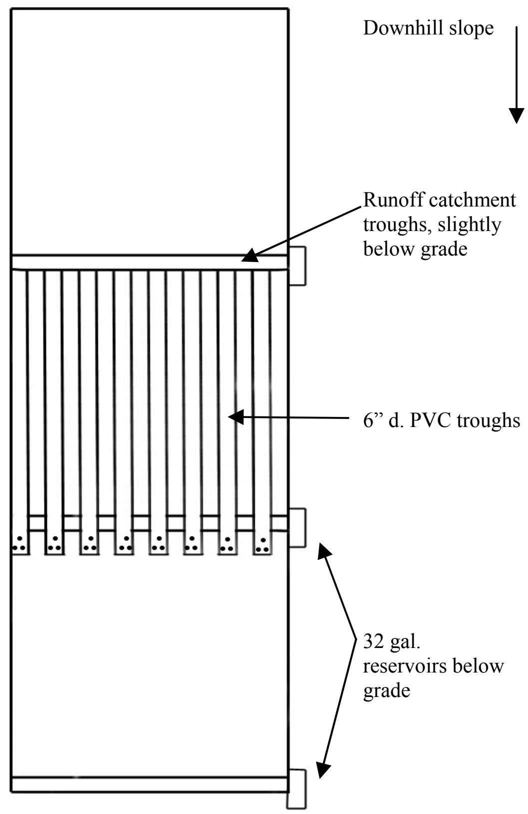
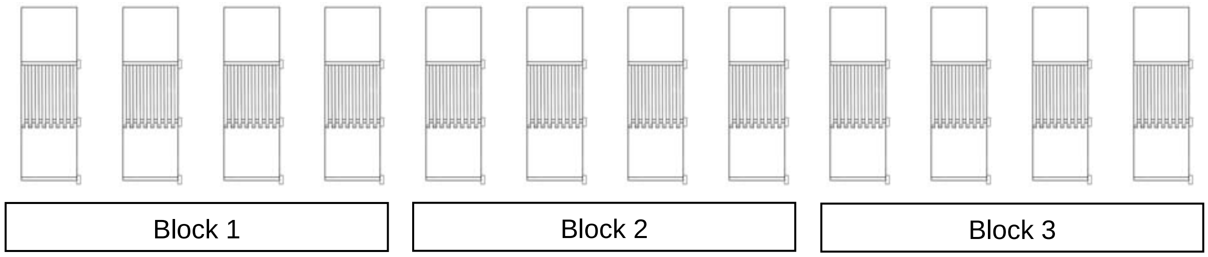


Figure 2.1. Diagram of a triplicate plot to provide urban landscape experimental areas with 100% (top), 50% (middle), and 150% (bottom) of natural precipitation. All three 2.4m x 2.4m (8 ft. x 8 ft.) subplots within the triplicate plot received the same landscape treatment.

a)



b)

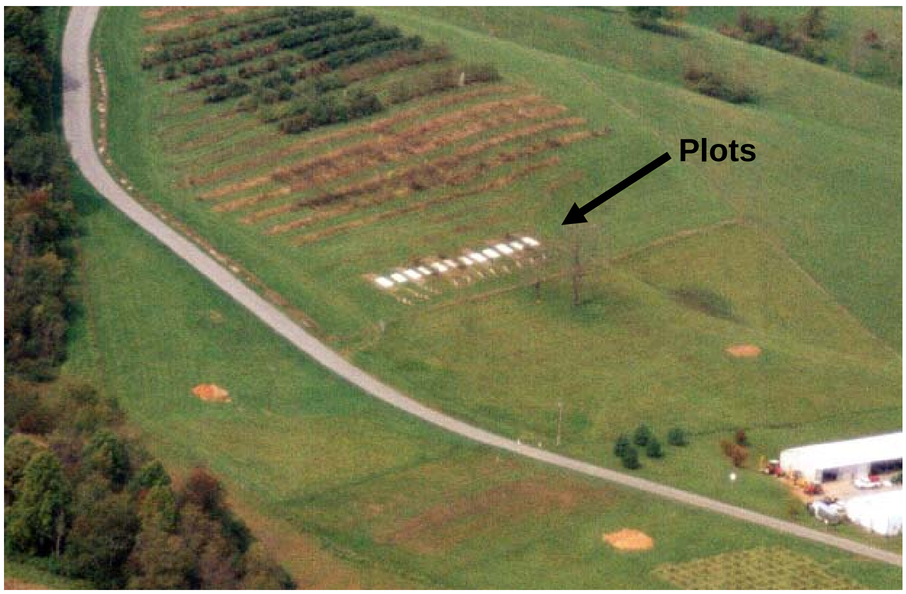
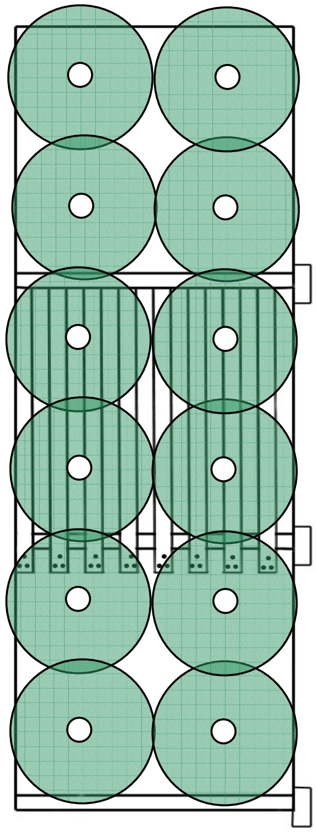


Figure 2.2. Diagram (a) and aerial photo (b) of 12 triplicate plots as located on the hillside site. Aerial photo courtesy of Joyce Shelton.

a)



b)

Figure 2.3. Diagram (a) and photo (b) of urban forest plot layout. Each 8 x 8 subplot was planted with four 3.2 cm diameter pin oak (Quercus palustris) trees. Canopy cover of individual trees at time of planting was 1 to 1.2 m in diameter.

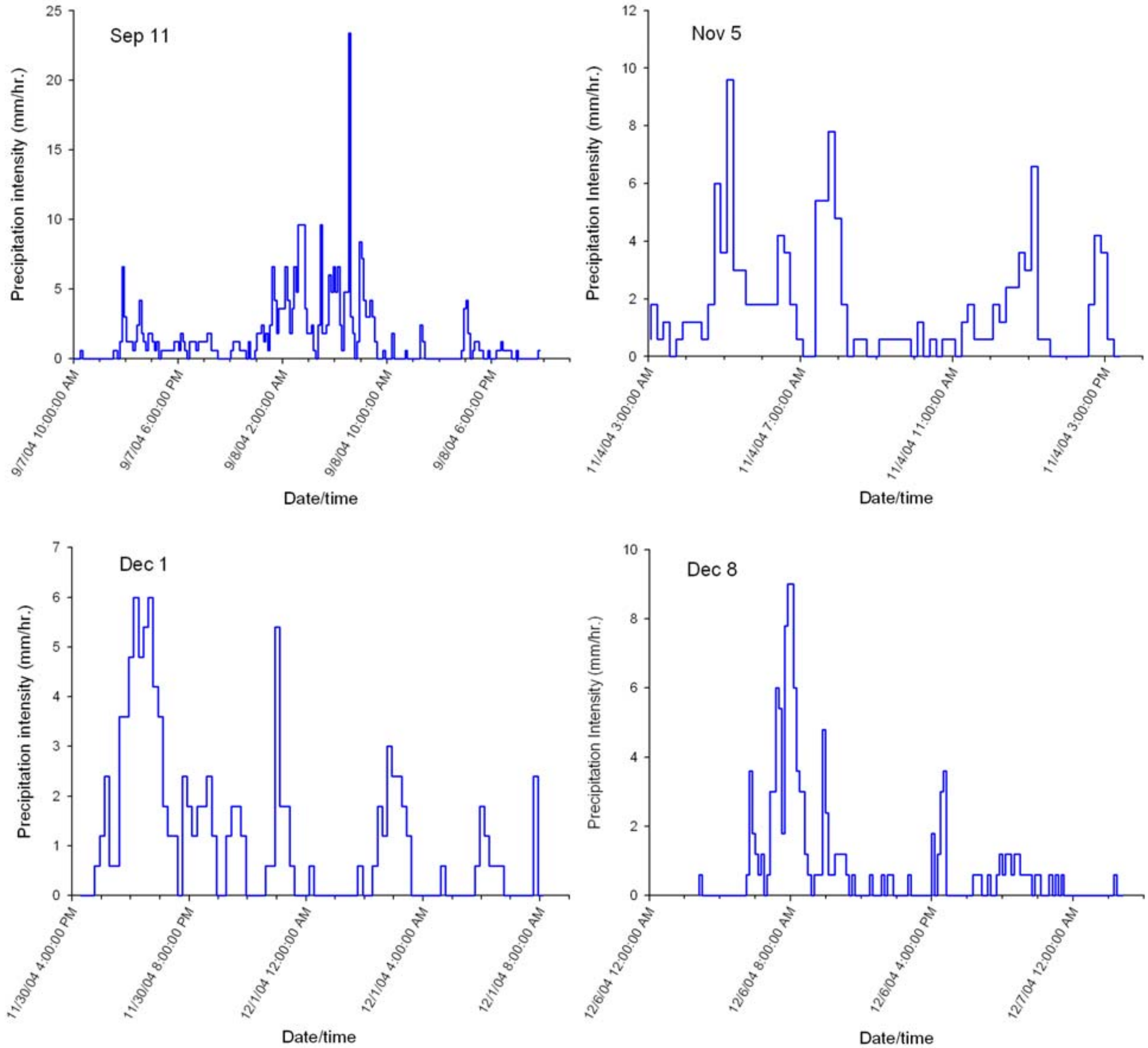


Figure 2.4. Rainfall intensity plots for Sep 11, Nov 5, Dec 1, and Dec 8 rain events. Rainfall intensity measured at 10 minute intervals.

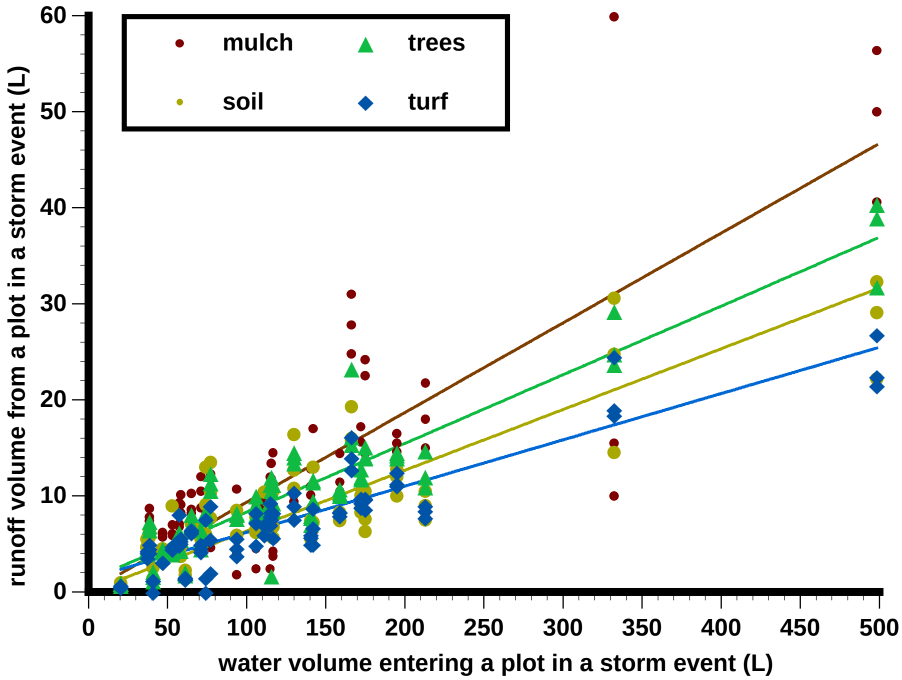


Figure 2.5. Scatterplot constructed of volume of water entering each plot on the x axis (taking into account precipitation manipulations), and volume of water collected as runoff from each plot on the y axis. Lines of best fit indicate turfgrass plots were more effective than other land covers at reducing runoff, especially at higher volumes of water entering the plots.

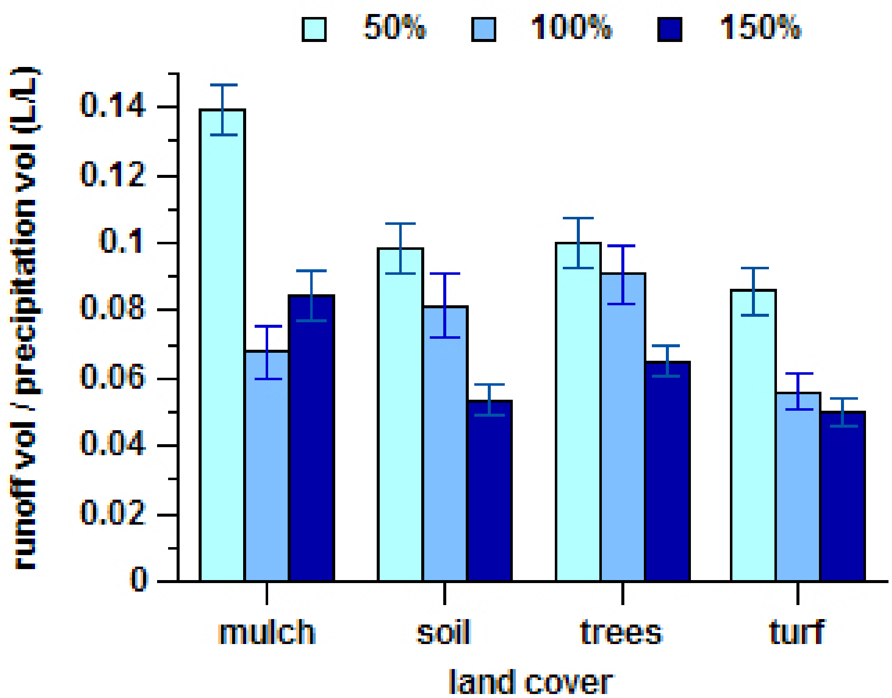


Figure 2.6. Runoff volume per precipitation volume received by land cover type and precipitation treatment. Error bars indicate standard error. "Trees" label refers to urban forest land cover treatment.

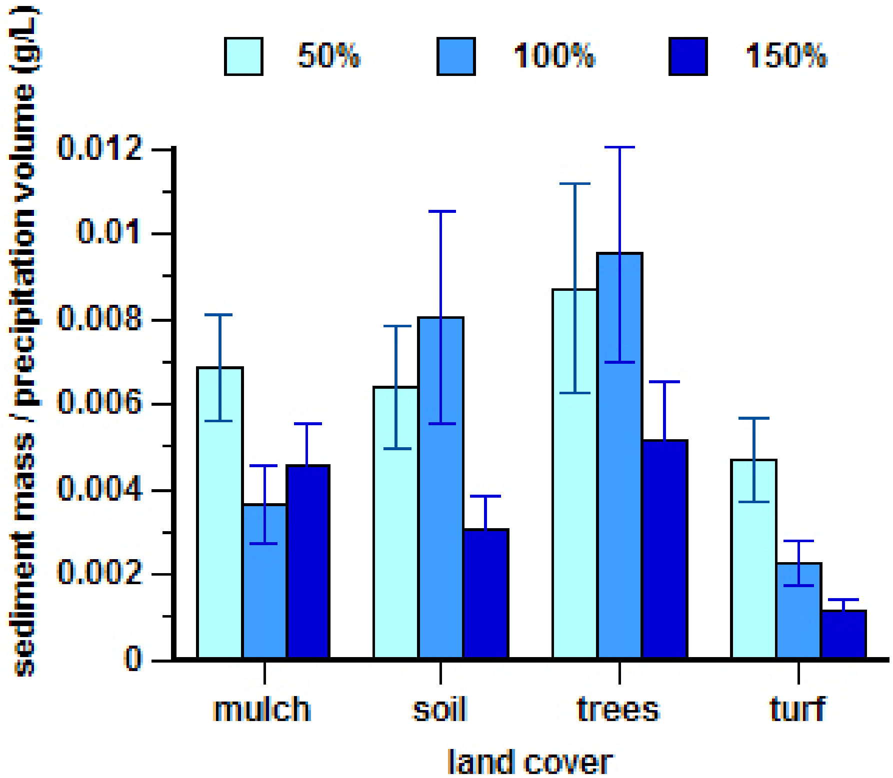


Figure 2.7. Sediment mass lost per precipitation volume received by land cover type and precipitation treatment. Error bars indicate standard error. “Trees” label refers to urban forest land cover treatment.

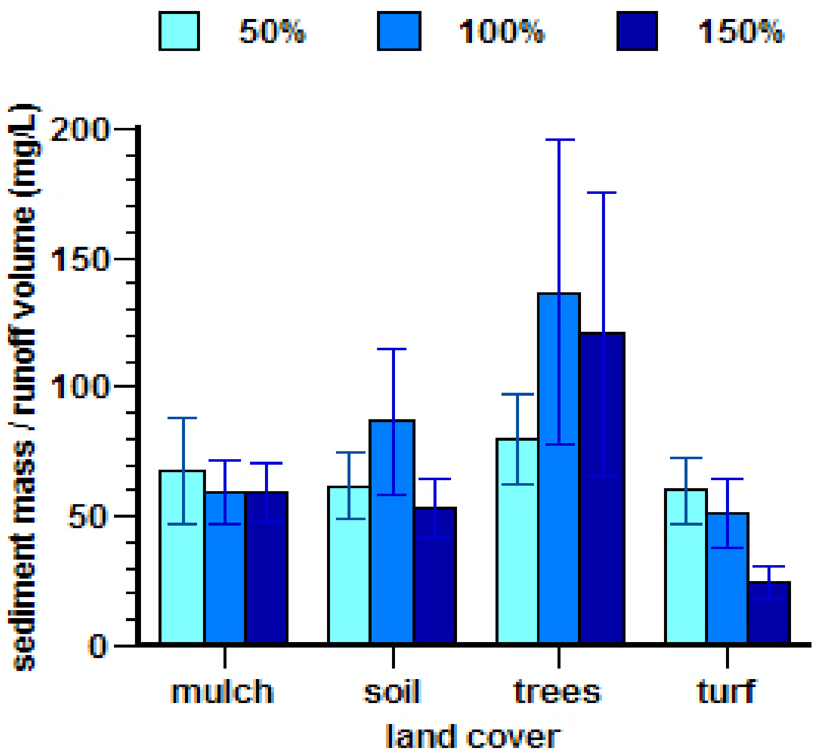


Figure 2.8. Sediment mass lost per runoff volume on a plot by land cover type and precipitation treatment. Error bars indicate standard error. “Trees” label refers to urban forest land cover treatment.

Vita

EDUCATION

Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA
Master of Science, Horticulture (December 2005)
Thesis: Quantifying the Potential for Non-Point Source Pollution in Model Urban Landscapes (Advisor: Gregory K. Eaton)

Colgate University, Hamilton, NY
Bachelor of Arts, Environmental Biology (May 2003)
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EXPERIENCE

Teaching Assistant, Department of Horticulture, Virginia Tech, Blacksburg, VA (August 2003-May 2005)

- Taught Indoor Plants course (Fall 2004, Spring 2005)
- Assisted professor with various aspects of Urban Horticulture course (Spring 2004)
- Prepared materials and equipment for Nursery Crops laboratory (Fall 2003)

Living Collections Intern, Arnold Arboretum of Harvard University, Jamaica Plain, MA (May-August 2002)

- Assisted curatorial staff with field checks, mapping, labeling, and specimen collection
- Maintained living collections with guidance of grounds crew
- Participated in classes on plant identification, cultural maintenance, and propagation

Teaching Assistant, Biology Department, Colgate University, Hamilton, NY (August-December 2001)

- Aided lab instructor in Introductory Biology laboratory
- Helped students with equipment use and laboratory exercises

CONFERENCES

Wolyniak, B.J. and G.K. Eaton. 2005. The potential for storm water runoff from model urban landscapes. Southern Nursery Association Research Conference, Georgia World Congress Center, Atlanta, GA.

Wolyniak, B.J. and G.K. Eaton. 2005. Using model urban and suburban landscapes to determine non-point source pollution potential. Mid-Atlantic Ecology Conference, Mid Atlantic Chapter of the Ecological Society of America, University of Maryland – Baltimore County, Baltimore, MD.

Wolyniak, B.J. and G.K. Eaton. 2004. Quantifying infiltration, runoff, and potential for non-point source pollution in model urban landscapes. Virginia Water Research Symposium, Virginia Tech, Blacksburg, VA.

HONORS

Dean's Award for Academic Excellence, Colgate University (Spring 2000, Spring 2002, Fall 2002, Spring 2003)

Beta Beta Beta Biological Honor Society, Upsilon Phi Chapter, Colgate University (Fall 2001-Spring 2003)