REDUCING NUTRIENT RUNOFF FROM GOLF COURSE FAIRWAYS USING MULTIPLE VEGETATIVE FILTER STRIPS

By

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INTRODUCTION

Chapter II of this thesis will be submitted for publication in Crop Science, published by Crop Science Society of America.

CHAPTER I

LITERATURE REVIEW

Literature Review

NUTRIENT RUNOFF AND TURFGRASS MANAGEMENT

The game of golf as we know it today began in Scotland at The Old Course at St. Andrews. Old Tom Morris was the greenkeeper at St. Andrews from 1865 to 1904 (Beard, 2002) and is believed to be the father of modern greenskeeping. Ever since the years Tom Morris roamed The Old Course at St. Andrews, turfgrass managers have been studying and improving the "art" of turfgrass science and management.

It is estimated that over 16,000 golf courses are in operation in the United States (National Golf Foundation, 1999). The average course contains about 12-16 ha of fairways that comprise the majority of maintained grass. Golf course fairways often border creeks, streams, ponds, lakes, and oceans. Consequently, nutrient runoff from golf course turf to surface water is an area of environmental concern. Nitrogen (N) and phosphorus (P) are the most widely used nutrients for the establishment and maintenance of golf course turf (Beard, 2002). Fertilizers allow turfgrass managers to effectively grow healthy and beautiful turfgrass stands. Fertilizers are typically "watered in" after application on a golf course either through irrigation or natural rainfall. Irrigation or natural rainfall will cause surface water runoff when irrigation or precipitation rates exceed soil water infiltration rates. Ideally, the turfgrass plants would take up all applied fertilizer nutrients. Unfortunately, sudden heavy rains or irrigation system malfunctions occasionally cause water and nutrient runoff.

Nitrogen can be taken up by the plant, lost to the atmosphere, stored in the soil, leached through the soil, or lost through surface runoff (Brady, 1990). Petrovic (1990) discussed the various fates of N fertilizers applied to turfgrass. There are many factors that influence the amount of N that a turfgrass plant can use. These include temperature, moisture, amount of available N, the source and rate of N applied, mowing height, and genetic makeup of the turfgrass plant. When more N is applied than the plant can take up, there is a potential for N loss to the environment. Nitrogen may be transported to surrounding streams or other bodies of water even if N is applied correctly. Nitrogen loss through surface runoff depends on such factors as soil moisture content, amount and timing of precipitation or irrigation, method and form of N application, slope, and various soil properties (Walker and Branham, 1992). According to Walker and Branham (1992), the greatest concentration of N in surface runoff will be found during the first significant runoff event after fertilization. Nitrogen is transported in surface runoff from turfgrass areas primarily as nitrate (NO_3^-) and ammonium (NH_4^+). Nitrogen in surface runoff at concentrations as low as 1 mg L^{-1} may lead to eutrophication. Eutrophication can be accelerated by an overabundance of P and N nutrients in surface waters. High nutrient levels cause an abundance of algae and aquatic plant blooms that deplete oxygen in the water body and may cause fish kills. High NO_3^- levels in drinking water is also a human health hazard. The United States Environmental Protection Agency has established a drinking water standard of 10 mg L^{-1} for NO_3-N (USEPA, 1976).

Generally, about 99% of the P in soils is unavailable for plant growth because less than 1% of soil P is in the soluble or available form for plant uptake. The availability of P depends on the following: soil pH; the amount of soluble iron (Fe), aluminum (Al), and manganese (Mn) in the soil; the amount of Fe, Al, and Mn-containing minerals in the soil; the amount of calcium (Ca) and Ca minerals in the soil; the amount and rate of decomposition of organic matter; and the microorganisms in the soil (Brady, 1990).

Fertilizers are thus important as a source of plant available P. There is no significant loss of soil P due to leaching or through gaseous forms, but the addition of soluble P fertilizers increases the risk of P loss in surface runoff. Phosphorus transport in surface runoff is affected by factors including rainfall or irrigation amount, intensity and duration of rainfall or irrigation, soil moisture, soil texture, slope, fertilizer application rate, and fertilizer formulation (Walker and Branham, 1992). Walker and Branham (1992) state that P transport will be greatest following the first significant precipitation event after fertilization. The researchers agree that P in surface runoff from golf course turf areas is primarily transported as HPO_4^- and $H_2PO_4^-$ which is also called dissolved reactive phosphorus (DRP) and can contribute to eutrophication of surface waters at concentrations as low as 25 $\mu g\ L^{-1}$. Most research has focused on the reduction of P loss to surface waters because P is typically the limiting factor for eutrophication of surface waters (Sharpley et al., 2000). Research has suggested that P loss from agricultural fields may represent a large amount of P input to surface waters and therefore control of P transport to surface waters is vital to reducing eutrophication (Sharpley and Rekolainen, 1997).

TURFGRASS NUTRIENT MANAGEMENT

Soil testing reveals nutrient availability in soils, therefore, it is useful for preventing nutrient deficiencies and over fertilization. Beard (2002) states that soil testing is helpful for assessing P, but is not effective for determining N status on golf courses. Nitrogen tends to give an immediate, favorable response when correctly applied to turfgrass. This favorable greening effect may encourage golf course managers to overapply fertilizer nutrients. Even when turf managers correctly apply fertilizer, there is still potential for nutrient runoff when fertilization is followed by heavy irrigation or a precipitation event.

FERTILIZER AND TURFGRASS MANAGEMENT

Kunimatsu et al. (1999) studied the loading rates of nutrients discharged from a golf course in Japan. Samples were taken from a stream that ran from a forested basin through the golf course. They found that an increase in nutrient discharge from the stream was due primarily to the N, P and K applied to the golf course as fertilizer. They also found that loading rates of total N and total P on the golf course were 2.5 and 23 times greater, respectively, than those found on the forested basin.

Walker and Branham (1992) thoroughly reviewed the impact of fertilization on golf course areas. Nitrogen fertilizer is divided into two groups: quick release and slow release. Quick release N is the most soluble form of N fertilizer. Urea, ammonium nitrate, ammonium sulfate, ammonium phosphates, and potassium nitrates are examples (Turgeon, 1999). Urea is commonly applied to bermudagrass (*Cynodon* spp.) golf course fairways and contains about 46% N. Typically on a bermudagrass golf course fairway, N will be applied throughout the growing season at a rate of 49 kg ha^{-1} mo^{-1}. Urea is highly soluble in water and N loss may occur by leaching (Petrovic, 1990), surface water runoff (Cole et al., 1997), or volatilization. Phosphorus fertilizers are primarily derived from rock phosphate. Triple superphosphate, a common fertilizer P source, is made by treating rock phosphate with phosphoric acid and contains about 46% phosphorus pentoxide (P_2O_5) or 20% P (Brady, 1990). Triple superphosphate is highly soluble in water and may be found in surface water runoff when applied to bermudagrass golf course fairways (Cole, et al. 1997). Phosphorus fertilizers may be applied to bermudagrass golf course fairways at rates as high as 24.4 kg P_2O_5 ha^{-1} mo^{-1}.

VEGETATIVE FILTER STRIPS

The United States Department of Agriculture Natural Resources Conservation Service defines conservation buffers as small areas or strips of land in permanent vegetation designed to intercept pollutants and manage other environmental concerns (USDA-NRCS, 2001). Buffers include the following: filter strips, riparian buffers, grassed waterways, shelterbelts, windbreaks, contour grass strips, cross-wind trap strips, field borders and other vegetative barriers. A properly established filter strip may help to reduce or eliminate the movement of sediments (Barfield et al., 1979; Hayes et al., 1979; Gross et al. 1990; Gross et al. 1991), pesticides (Baker et al., 2000; Baird et al., 2000) and nutrients (Baird et al., 2000; Gross et al. 1990). Buffers also protect wildlife and the environment surrounding agricultural fields. Buffers may enhance fish and wildlife habitat, improve or prevent further degradation of water quality, improve soil quality, reduce flooding, conserve energy, and conserve biodiversity (USDA-NRCS, 2001). Grass vegetation is recommended for filter strips (USDA-NRCS, 1997). Vegetative filter strips (VFS) are also called grassed buffer strips and are areas of permanent grassed vegetation that serve to prevent or reduce surface runoff of chemicals and nutrients from agricultural lands, golf courses, and residential landscapes. Vegetative filter strip use has been widely studied in agricultural settings and have been shown to reduce nutrient losses from agricultural lands (Arora et al., 1996; Baker et al., 2000; Chaubey et al., 1994, Dillaha et al., 1989; Edwards et al., 1997 and 1996; Hawkins et al., 1998; Heathwaite et al., 1998; Lee et al., 1999; Lim et al., 1998; Magette, et al., 1989; Mendez et al., 1999; Mersie et al., 1999; Misra et al., 1996; Patty et al., 1997; Robinson et al., 1996; Sanderson et al., 2001; Schmitt et al., 1999; Srivastava et al., 1996). Limited research is found in the area of golf course management and vegetative filter strip performance.

VEGETATIVE FILTER STRIPS AND GOLF COURSE TURF

Baird et al. (2000) reported that VFS were effective chemical filters in a golf course setting. Cole et al. (1997) studied runoff from bermudagrass plots simulating golf course fairways that were bordered by VFS of differing width (0, 1.2, 2.4, and 4.9 m) and mowing height (1.3, 3.8, 7.6 cm). Average slope at the research site was 6%. Urea and super triplephosphate fertilizers were applied at normal rates. They concluded that one should maintain vegetative buffers bordering golf course fairways at a height of at least 7.6 cm. They also found that vegetative buffers are effective for reducing nutrient runoff when compared to plots without vegetative buffers. Their findings indicated that while a vegetative buffer is effective for reducing nutrient runoff from golf course fairways, under certain conditions the concentrations of nutrients from all treatments were above the levels that could cause eutrophication of surface waters. When the soil was not saturated, less than 2% of applied nutrients were detected in the surface runoff. Nominal losses occurred when 79 mm of simulated rainfall was applied 24 hours following fertilization.

Krenitsky et al. (1998) compared natural and man-made erosion control materials. They found that tall fescue (*Festuca arundinacea* Schreb. var. 'Falcon') sod was an effective material for delaying the start of runoff and decreasing total runoff volume. Linde et al. (1994) also demonstrated that turf was an effective buffer for reducing surface water runoff. Creeping bentgrass (*Agrostis palustris* Huds.) and perennial ryegrass (*Lolium perenne* L.) plots of 123 m^2 were maintained as golf course fairways. These researchers reported that creeping bentgrass reduced surface water runoff more effectively than perennial ryegrass. However, both grasses were effective for reducing total nutrient runoff from applied fertilizer. Water sample concentrations of NO_3-N did not exceed 7.2 mg L^{-1} and dissolved P did not exceed 6 mg L^{-1}. They concluded that fertilizer nutrients did not move in runoff or leachate collectors in amounts that were greater than the concentrations found in the irrigation water under the conditions that were studied, yet they did not report background irrigation water nutrient concentrations. However, N and P concentrations found in runoff water samples were above levels that cause eutrophication of surface waters. Linde et al. (1995) tested differences in creeping bentgrass and perennial ryegrass turf for the reduction of surface water runoff. The researchers concluded that creeping bentgrass was more effective for reducing surface water runoff than perennial ryegrass because creeping bentgrass had a higher water-holding capacity and increased hydraulic resistance. Linde et al. (1997) found that sediments in runoff were low even after vertical mowing in turf. Again they compared creeping bentgrass and perennial ryegrass turf maintained as a golf course fairway. They also found that nutrient transport of dissolved P and total Kjeldahl-N increased during runoff events when irrigation was applied 8 hours after fertilization. For all other runoff events throughout the experiment, nutrients in runoff were lower. They concluded that fertilizer applications to a saturated soil followed by irrigation or precipitation may lead to off-site movement of nutrients. Linde et al. (1998) found that creeping bentgrass was more effective for reducing surface runoff when compared with perennial ryegrass after vertical mowing and earthworm activity. They concluded that selection of a higher-density, thatchy turf would be more effective for reducing surface runoff from golf course fairways when compared with a lower-density turf that produces little thatch.

Harrison et al. (1993) tested nutrients and pesticide concentration in runoff from sodded Kentucky bluegrass (*Poa pratensis* L.) and two seeded commercial mixtures. Plots were fertilized with N, P and K in a typical maintenance program for golf course turf in the northeast United States. Irrigation was applied one week prior to and two days following fertilizer applications at rates of 75 mm h^{-1} and 150 mm h^{-1} for one hour. The researchers reported that nutrient concentrations in runoff remained low throughout the experiment and generally were no higher than the concentrations found in the irrigation water. However, N concentrations were as high as 5 mg L^{-1} and dissolved P concentrations were as high as 6 mg L^{-1}. Both N and P nutrient concentrations were above those that cause eutrophication of surface waters. The researchers concluded that under the conditions studied, nutrient runoff from established turfgrass areas is low due to low runoff water volume and is not affected by establishment method. However, nutrient concentration levels were high enough to cause eutrophication in every runoff event studied.

Gross et al. (1990) studied nutrient and sediment loss from sodded tall fescue (*Festuca arundinacea* Schreb.)/Kentucky bluegrass (*Poa pratensis* L.) plots. The plots were sodded on land that was previously cropped to tobacco (*Nicotiana tabacum* L.). Slope at the site was 5 to 7%. Plots were fertilized with either urea dissolved in water as a liquid application or urea as a granular application at a rate of 220 kg N ha^{-1} yr^{-1}. Control plots were not fertilized. Nutrient and sediment losses were low for all replications. They concluded that nutrient and sediment runoff from turfgrass areas is low, especially when compared with the previously cropped tobacco runoff study. Gross et al. (1991) studied runoff and sediment losses from tall fescue stands of various density under simulated rainfall conditions. Plots were established at seeding rates of 0, 98, 244, 390, and 488 kg ha^{-1} in September 1986. Simulated rainfall was applied at intensities of 76, 94 and 130 mm hr^{-1} in June 1987. The highest runoff volume was observed for the non-seeded plots for each rainfall intensity. Runoff volume was not statistically different among the 98, 244, 390, and 488 kg ha^{-1} seeding rates. The researchers also recorded visual means density and tiller counts. They concluded that even low-density turfgrass stands can significantly reduce surface water runoff from well-maintained turf areas.

It has been shown that turfgrass can be an effective filter of sediment and chemicals in highly maintained turfgrass areas. The predominant factors in determining the amount of nutrient runoff from golf courses is soil moisture content before and after fertilization, soil moisture content before precipitation or irrigation, type and amount of fertilizer applied, slope, and distance from the turfgrass area to surface waters. While previous studies have indicated that turfgrass is helpful for reducing or preventing nutrient runoff from well maintained turf areas, little research has been completed concerning vegetative filter strip performance. Public concern of golf course management and its impacts on the environment demand that researchers continue to develop strategies to mitigate the potentially harmful effects of nutrient runoff from golf courses. This research will demonstrate the potential fates of nutrients applied to golf course fairways under heavy precipitation scenarios and will provide needed information to further reduce nutrient runoff from highly maintained turf areas.

Unlike previous research, this study will utilize very large plot areas that can simulate runoff from more than half the width of a normal golf course fairway. Previous research (Cole, et al., 1997) showed that VFS reduce nutrient runoff from simulated golf course fairways when compared to plots without VFS. The researchers concluded that one should maintain VFS of at least 7.6 cm. However, the researchers found no relationship between differing VFS width and N concentrations in runoff water. These results suggest that the initial barrier provided by the VFS was more important for nutrient runoff reduction than VFS width or height. A graduated VFS mowed at increasingly higher heights may further inhibit nutrient runoff by presenting a series of obstacles. The concept of multiple VFS of increasing heights may reduce nutrient runoff due to the increased hydraulic resistance of the turf created by the series of obstacles. Previous research has shown that nutrient or surface water runoff increases as soil moisture levels increase (Cole, et al., 1997, Linde, et al., 1997). Unlike prior research, this study will maintain soil moisture levels at field capacity before a precipitation event. This will help determine fates of nutrients under extreme conditions i.e. fertilizer applied to field capacity soils followed by heavy precipitation. This will also provide information for future research to be conducted at OSU. Future research at the site may study the impact of antecedent soil moisture and application timing prior to rainfall on nutrient runoff potential and investigate the potential use of computer models to determine fertilizer fate under golf course conditions.

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CHAPTER II

REDUCING NUTRIENT RUNOFF FROM GOLF COURSE FAIRWAYS USING MULTIPLE VEGETATIVE FILTER STRIPS

Reducing Nutrient Runoff From Golf Course Fairways Using Vegetative Filter Strips

J. Q. Moss, G. E. Bell*, M. A. Kizer, M. E. Payton, H. Zhang, and D. L. Martin

Fairways comprise the majority of maintained grass on golf courses and often border creeks, streams, ponds, lakes, and oceans. Bermudagrass (*Cynodon* spp.) is a commonly used turf for golf course fairways and is fertilized at rates as high as 49 kg N ha^{-1} mo^{-1} and 24 kg P_2O_5 ha^{-1} mo^{-1} during the growing season. Consequently, nutrient runoff from golf course turf to surface water is an area of environmental concern. Vegetative Filter Strips (VFS) are areas of permanent grassed vegetation that serve to prevent or reduce surface runoff of chemicals and nutrients from agricultural lands, golf courses, and residential landscapes. Little research has been done concerning VFS performance on golf course areas. The objective of this study was to investigate the influence of multiple VFS of increasing height for reduction of nutrient runoff from bermudagrass golf course fairways. Simulated (irrigation applied at a rate of 51 mm h^{-1} for 1.5 hr) and natural rainfall events were observed for differences between single VFS and multiple VFS of increasing height. There were no significant differences between single VFS and

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multiple VFS of increasing height for the reduction of NO_3-N, NH_4-N, and dissolved reactive phosphorus (DRP) when urea and triple superphosphate were applied to bermudagrass golf course fairways. Multiple VFS of increasing height did increase time to initiation of runoff by 53% when compared to single VFS during natural rainfall events, but there were no significant differences in total nutrient load during both simulated and natural rainfall events between the two treatments. There were no significant differences in NO_3-N, NH_4-N, and DRP concentrations found in runoff water between single VFS and multiple VFS of increasing height. Nitrate-N concentrations in runoff did not exceed the US Environmental Protection Agency drinking water standard of 10 mg L^{-1} regardless of treatment. Although percent loss of applied N and P from fertilizer was low, NO_3-N, NH_4-N, and DRP concentrations found in surface water runoff from bermudagrass fairways were higher than those previously found to contribute to eutrophication of surface waters regardless of treatment. Further research is thus needed to develop management strategies that may reduce total runoff volume and nutrient concentrations found in surface water runoff from golf course areas.

INTRODUCTION

It is estimated that over 16,000 golf courses are in operation in the United States (National Golf Foundation, 1999). Fairways comprise about 12-16 ha of area on these courses and the majority of maintained grass. Golf course fairways often border creeks, streams, ponds, lakes, and oceans. Consequently, nutrient runoff from golf course turf to surface water is an area of environmental concern. Nitrogen (N) and phosphorus (P) are two of the most important nutrients used for the establishment and maintenance of golf course turf (Beard, 2002). Fertilizers are typically "watered in" after application on a golf course either through irrigation or natural rainfall. Irrigation or natural rainfall will cause surface water runoff when irrigation or precipitation rates exceed soil water infiltration rates. Ideally, the turfgrass plants would take up all fertilizer nutrients that are applied. Unfortunately, sudden heavy rains or irrigation system malfunctions occasionally cause water and nutrient runoff.

Nitrogen can be taken up by the plant, lost to the atmosphere, stored in the soil, leached through the soil, or lost through surface runoff (Brady, 1990). Petrovic (1990) discussed the various fates of N fertilizers applied to turfgrass. There are many factors that influence the amount of N that a turfgrass plant can use. These include temperature, moisture, amount of available N, the source and rate of N applied, mowing height, and genetic makeup of the turfgrass plant. Nitrogen loss through surface runoff depends on such factors as soil moisture content, amount and timing of precipitation or irrigation, method and form of N application, slope, and various soil properties (Walker and Branham, 1992). According to Walker and Branham (1992), the greatest concentration of N in surface runoff will be found during the first significant runoff event after fertilization. Nitrogen is transported in surface runoff from turfgrass areas primarily as nitrate (NO_3^-) and ammonium (NH_4^+). Nitrogen in surface runoff at concentrations as low as 1 mg L^{-1} may lead to eutrophication. Eutrophication can be accelerated by an overabundance of P and N nutrients in surface waters. High nutrient levels cause an abundance of algae and aquatic plant blooms that deplete oxygen in the water body and may cause fish kills. High NO_3^- levels in drinking water are also a human health hazard.

The United States Environmental Protection Agency has established a drinking water standard of 10 mg L^{-1} for NO_3-N (USEPA, 1976).

Generally, about 99% of the P in soils is unavailable for plant growth because less than 1% of soil P is in the soluble or available form for plant uptake. The availability of P depends on the following: soil pH; the amount of soluble iron (Fe), aluminum (Al), and manganese (Mn) in the soil; the amount of Fe, Al, and Mn-containing minerals in the soil; the amount of calcium (Ca) and Ca minerals in the soil; the amount and rate of decomposition of organic matter; and the microorganisms in the soil (Brady, 1990). Phosphorus transport in surface runoff is affected by factors including rainfall or irrigation amount, intensity and duration of rainfall or irrigation, soil moisture, soil texture, slope, fertilizer application rate, and fertilizer formulation (Walker and Branham, 1992). Walker and Branham (1992) state that P transport will be greatest following the first significant precipitation event after fertilization. The researchers agree that P in surface runoff from golf course turf areas is primarily transported as HPO_4^- and $H_2PO_4^-$ which is also called dissolved reactive phosphorus (DRP) and can contribute to eutrophication of surface waters at concentrations as low as 25 μg L^{-1}. Most research has focused on the reduction of P loss to surface waters because P is typically the limiting factor for eutrophication of surface waters (Sharpley et al., 2000). Research has suggested that P loss from agricultural fields may represent a large amount of P input to surface waters and, therefore, control of P transport to surface waters is vital to reducing eutrophication (Sharpley and Rekolainen, 1997).

Kunimatsu et al. (1999) studied the loading rates of nutrients discharged from a golf course in Japan. Samples were taken from a stream that ran from a forested basin through the golf course. They found that an increase in nutrient discharge from the stream was due primarily to the N, P and K applied to the golf course as fertilizer. They also found that loading rates of total N and total P on the golf course were 2.5 and 23 times greater, respectively, than those found on the forested basin.

Walker and Branham (1992) thoroughly reviewed the impact of fertilization on golf course areas. Nitrogen fertilizer is divided into two groups: quick release and slow release. Quick release N is the most soluble form of N fertilizer. Urea is commonly applied to bermudagrass (*Cynodon* spp.) golf course fairways and contains about 46% N (Turgeon, 1999). Typically on a bermudagrass golf course fairway, N will be applied throughout the growing season at a rate of 49 kg ha^{-1} mo^{-1}. Urea is highly soluble in water and N loss may occur by leaching (Petrovic, 1990), surface water runoff (Cole et al., 1997), or volatilization. Triple superphosphate, a common fertilizer P source, is made by treating rock phosphate with phosphoric acid and contains about 46% phosphorus pentoxide (P_2O_5) or 20% P (Brady, 1990). Triple superphosphate is highly soluble in water and may be found in surface water runoff when applied to bermudagrass golf course fairways (Cole, et al. 1997). Phosphorus fertilizers may be applied to bermudagrass golf course fairways at rates as high as 24.4 kg P_2O_5 ha^{-1} mo^{-1}.

A properly established filter strip may help to reduce or eliminate the movement of sediments (Barfield et al., 1979; Hayes et al., 1979; Gross et al. 1990; Gross et al. 1991), pesticides (Baker et al., 2000; Baird et al., 2000) and nutrients (Baird et al., 2000; Gross et al. 1990). Grass vegetation is recommended for filter strips (USDA-NRCS, 1997). Vegetative filter strips (VFS) are also called grassed buffer strips and are areas of permanent grassed vegetation that serve to prevent or reduce surface runoff of chemicals and nutrients from agricultural lands, golf courses, and residential landscapes. Vegetative filter strip use has been widely studied in agricultural settings and have been shown to reduce nutrient losses from agricultural lands (Arora et al., 1996; Baker et al., 2000; Chaubey et al., 1994, Dillaha et al., 1989; Edwards et al., 1997 and 1996; Hawkins et al., 1998; Heathwaite et al., 1998; Lee et al., 1999; Lim et al., 1998; Magette, et al., 1989; Mendez et al., 1999; Mersie et al., 1999; Misra et al., 1996; Patty et al., 1997; Robinson et al., 1996; Sanderson et al., 2001; Schmitt et al., 1999; Srivastava et al., 1996). Limited research is found in the area of golf course management and vegetative filter strip performance.

Baird et al. (2000) reported that VFS were effective chemical filters in a golf course setting. Cole et al. (1997) studied runoff from bermudagrass plots simulating golf course fairways that were bordered by VFS of differing width (0, 1.2, 2.4, and 4.9 m) and mowing height (1.3, 3.8, 7.6 cm). Average slope at the research site was 6%. Urea and super triplephosphate fertilizers were applied at normal rates. They concluded that one should maintain vegetative buffers bordering golf course fairways at a height of at least 7.6 cm. They also found that vegetative buffers are effective for reducing nutrient runoff when compared to plots without vegetative buffers. Their findings indicated that while a vegetative buffer is effective for reducing nutrient runoff from golf course fairways, under certain conditions the concentrations of nutrients from all treatments were above the levels that could cause eutrophication of surface waters. When the soil was not saturated, less than 2% of applied nutrients were detected in the surface runoff. Nominal losses occurred when 79 mm of simulated rainfall was applied 24 hours following fertilization.

Krenitsky et al. (1998) compared natural and man-made erosion control materials. They found that tall fescue (*Festuca arundinacea* Schreb. var. 'Falcon') sod was an effective material for delaying the start of runoff and decreasing total runoff volume. Linde et al. (1994) also demonstrated that turf was an effective buffer for reducing surface water runoff. Creeping bentgrass (*Agrostis palustris* Huds.) and perennial ryegrass (*Lolium perenne* L.) plots of 123 m^2 were maintained as golf course fairways. These researchers reported that creeping bentgrass reduced surface water runoff more effectively than perennial ryegrass. However, both grasses were effective for reducing total nutrient runoff from applied fertilizer. Water sample concentrations of NO_3-N did not exceed 7.2 mg L^{-1} and dissolved P did not exceed 6 mg L^{-1}. They concluded that fertilizer nutrients did not move in runoff or leachate collectors in amounts that were greater than the concentrations found in the irrigation water under the conditions that were studied, yet they did not report background irrigation water nutrient concentrations. However, N and P concentrations found in runoff water samples were above levels that cause eutrophication of surface waters. Linde et al. (1995) tested differences in creeping bentgrass and perennial ryegrass turf for the reduction of surface water runoff. The researchers concluded that creeping bentgrass was more effective for reducing surface water runoff than perennial ryegrass because creeping bentgrass had a higher water-holding capacity and increased hydraulic resistance. Linde et al. (1997) found that sediments in runoff were low even after vertical mowing in turf. Again they compared creeping bentgrass and perennial ryegrass turf maintained as a golf course fairway. They also found that nutrient transport of dissolved P and total Kjeldahl-N increased during runoff events when irrigation was applied 8 hours after fertilization. For all other runoff events throughout the experiment, nutrients in runoff were lower. They concluded that fertilizer applications to a saturated soil followed by irrigation or precipitation may lead to off-site movement of nutrients. Linde et al. (1998) found that creeping bentgrass was more effective for reducing surface runoff when compared with perennial ryegrass after vertical mowing and earthworm activity. They concluded that selection of a higher-density, thatchy turf would be more effective for reducing surface runoff from golf course fairways when compared with a lower-density turf that produces little thatch.

Harrison et al. (1993) tested nutrients and pesticide concentration in runoff from sodded Kentucky bluegrass (*Poa pratensis* L.) and two seeded commercial mixtures. Plots were fertilized with N, P and K in a typical maintenance program for golf course turf in the northeast United States. Irrigation was applied one week prior to and two days following fertilizer applications at rates of 75 mm h^{-1} and 150 mm h^{-1} for one hour. The researchers reported that nutrient concentrations in runoff remained low throughout the experiment and generally were no higher than the concentrations found in the irrigation water. However, N concentrations were as high as 5 mg L^{-1} and dissolved P concentrations were as high as 6 mg L^{-1}. Both N and P nutrient concentrations were above those that cause eutrophication of surface waters. The researchers concluded that under the conditions studied, nutrient runoff from established turfgrass areas is low due to low runoff water volume and is not affected by establishment method. However, nutrient concentration levels were high enough to cause eutrophication in every runoff event studied.

Gross et al. (1990) studied nutrient and sediment loss from sodded tall fescue (*Festuca arundinacea* Schreb.)/Kentucky bluegrass (*Poa pratensis* L.) plots. The plots were sodded on land that was previously cropped to tobacco (*Nicotiana tabacum* L.). Slope at the site was 5 to 7%. Plots were fertilized with either urea dissolved in water as a liquid application or urea as a granular application at a rate of 220 kg N ha^{-1} yr^{-1}. Control plots were not fertilized. Nutrient and sediment losses were low for all replications. They concluded that nutrient and sediment runoff from turfgrass areas is low, especially when compared with the previously cropped tobacco runoff study. Gross et al. (1991) studied runoff and sediment losses from tall fescue stands of various density under simulated rainfall conditions. Plots were established at seeding rates of 0, 98, 244, 390, and 488 kg ha^{-1} in September 1986. Simulated rainfall was applied at intensities of 76, 94 and 130 mm hr^{-1} in June 1987. The highest runoff volume was observed for the non-seeded plots for each rainfall intensity. Runoff volume was not statistically different among the 98, 244, 390, and 488 kg ha^{-1} seeding rates. The researchers also recorded visual means density and tiller counts. They concluded that even low-density turfgrass stands can significantly reduce surface water runoff from well-maintained turf areas when compared to non-seeded plots.

It has been shown that turfgrass can be an effective filter of sediment and chemicals in highly maintained turfgrass areas. The predominant factors in determining the amount of nutrient runoff from golf courses are soil moisture content before and after fertilization, soil moisture content before precipitation or irrigation, type and amount of fertilizer applied, slope, and distance from the turfgrass area to surface waters. While previous studies have indicated that turfgrass is helpful for reducing or preventing nutrient runoff from well maintained turf areas, little research has been completed concerning vegetative filter strip performance. Researchers have suggested that nutrient runoff from highly maintained turfgrass areas is low, but N and P concentrations in runoff water were high enough to cause eutrophication in all previous studies to date. Public concern of golf course management and its impacts on the environment demand that researchers continue to develop strategies to mitigate the potentially harmful effects of nutrient runoff from golf courses, especially when a surface water body is nearby. This research will demonstrate the potential fates of nutrients applied to golf course fairways under heavy precipitation scenarios and will provide needed information to further reduce nutrient runoff from highly maintained turf areas.

Unlike previous research, this study will utilize very large plot areas that can simulate runoff from more than half the width of a normal golf course fairway. Previous research (Cole, et al., 1997) showed that VFS reduce nutrient runoff from simulated golf course fairways when compared to plots without VFS. The researchers concluded that one should maintain VFS of at least 7.6 cm. However, the researchers found no relationship between differing VFS width and N concentrations in runoff water. These results suggest that the initial barrier provided by the VFS was more important for nutrient runoff reduction than VFS width or height. A graduated VFS mowed at increasingly higher heights may further inhibit nutrient runoff by presenting a series of obstacles. The concept of multiple VFS of increasing heights may reduce nutrient runoff by reducing surface water runoff due to the increased hydraulic resistance of the turf created by the series of obstacles. Previous research has shown that nutrient or surface water runoff increases as soil moisture levels increase (Cole, et al., 1997, Linde, et al., 1997). Unlike prior research, this study will maintain soil moisture levels at field capacity before a precipitation event. This will help determine fates of nutrients under extreme conditions i.e. fertilizer applied to field capacity soils followed by heavy precipitation. This will also provide information for future research to be conducted at Oklahoma State University. Future research at the site may study the impact of antecedent soil moisture and application timing prior to rainfall on nutrient runoff potential and investigate the potential use of computer models to determine fertilizer fate under golf course conditions.

The objective of this study was to investigate the influence of multiple VFS of increasing height for reduction of nutrient runoff from bermudagrass golf course fairways.

MATERIALS AND METHODS

This research was conducted at the Oklahoma State University Turfgrass Research Center in Stillwater, OK during the summer of 2001. The soil at the site was Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) with an infiltration rate of less than 13 mm h^{-1}. The site was divided into three large blocks (595 m^2) each consisting of two experimental units for a total of six large plots with dimensions of 12.2 m wide by 24.4 m long (Fig. 1). Each plot was graded to a uniform 5% slope with a box blade and transit level and sodded with 'U-3' bermudagrass in the summer of 1998. The plots were separated by earthen mounds that prevented surface water from running into adjacent plots. The six plots consisted of an area of simulated golf course fairway (12.2 m wide by 18.9 m long) bordered by an area of VFS (12.2 m wide by 5.5 m long) at the bottom of the slope. The simulated fairway area was maintained at a mowing height of 1.3 cm. The fairway areas were rolled daily with a golf cart to simulate traffic. Three of the plots contained a simulated fairway followed by a VFS mowed at 5.1 cm. The other three plots were randomly assigned a simulated fairway bordered by a VFS mowed at increasing heights. The VFS in these experimental plots were divided into three equal sections (12.2 m wide by 1.83 m long) that were mowed at increasing heights of 2.5, 3.8 and 5.1 cm (Fig. 2). The VFS in these plots were mowed at increasing heights with decreasing elevation and VFS in all plots were maintained perpendicular to the slope. Fertilizer was applied only to the simulated golf course fairway area. Nitrogen was applied as urea at a rate of 48.8 kg N ha^{-1} per application. Phosphorus was applied as super triplephosphate at a rate of 24.4 kg P_2O_5 ha^{-1} per application. Fertilizer was applied a total of six times throughout the growing season. An initial application took place 4 hrs prior to a simulated rainfall event. Fertilizer was applied a second time after the completion of the simulated rainfall event to assess nutrient runoff during natural rainfall. Each individual plot was surrounded by six evenly spaced overhead irrigation sprinklers capable of producing an irrigation event of 51 mm hr^{-1}. Christiansen's coefficient of uniformity for each plot was determined using methods as described in ANSI/ASAE Standards 330.1 (ASAE, 1993). Irrigation for each simulated runoff event was applied at the maximum rate (51 mm hr^{-1}) for 1.5 hrs. The natural rainfall event amounts and lengths were as follows: replication one rainfall fell at a maximum rate of 33 mm hr^{-1} for 1.5 h, replication two rainfall fell at a maximum rate of 15 mm hr^{-1} for 2.5 h, and replication three rainfall fell at a maximum rate of 17 mm hr^{-1} for 2 h.

Each plot contained three evenly spaced CS615 Water Content Reflectometers (Campbell Scientific, Logan, UT; WCR) (Fig. 1). The WCR monitored the soil moisture content in each plot continually. Data collection was initiated for each individual plot every 60 min by an AM416 Relay Multiplexer (Campbell Scientific) and recorded using a CR10X Datalogger (Campbell Scientific). The datalogger was connected by modem to a central computer located in the Oklahoma State University Turfgrass Research Center where data were stored for interpretation. Soil moisture was recorded on the computer every hour and each plot was irrigated daily to maintain field capacity based on the average measure of the three WCR placed at high, medium, and low elevation in each plot.

Runoff on each plot was collected by a 15 cm trough that channeled water into a Parshall flume for flow measurement and sample collection (Fig. 3.). The collection troughs were made of polyvinylchloride pipe cut in half longways and were mounted on wooden support posts (10 by 10 by 60 cm long). The posts were buried in concrete below the soil frost line to stabilize the troughs. Each trough was covered by galvanized sheet metal mounted above a piece of angle iron that extended on top of the soil and over the edge of the trough across the bottom edge of each plot. The angle iron was secured to the soil with large landscape timber nails. Stainless steel bolts supported the galvanized cover 7.6 cm above the soil to allow collection of runoff while eliminating entry of irrigation or rainfall into the trough. The cover sloped from 7.6 cm above the soil on the edge facing the VFS to soil level over the trough effectively channeling irrigation or rainfall away from the collection sites. The angle iron and a galvanized shingle-type attachment channeled runoff water from each plot into the corresponding collection trough (Fig. 4.). The plot side of each angle iron was secured with paraffin wax to prevent water from running beneath the trough.

Isco 6700 portable samplers (Isco, Lincoln, NE) were secured to level concrete platforms located between each experimental block (Fig. 3.). Ultrasonic Modules (Isco 710) mounted over each Parshall flume used ultrasonic reflection to measure water level. The sampler was programmed to determine water flow rate from these water level measurements based on a pre-determined calibration of each Parshall flume. A pump in each sampler provided runoff sample collection through vinyl suction line tubing (0.95 cm) fitted with a screen strainer and extended into the Parshall flume. Samples were collected every 5 min for 1 h following runoff initiation. Time to initiation of runoff following initiation of irrigation or rainfall was calculated for each event and flow rate was measured every minute. A Rapid Transfer Device (Isco 581) enabled information transfer from samplers to the computer.

Water samples were analyzed for NO_3–N and NH_4–N using colorimetric methods by automated flow injection analysis and DRP using the phosphomolybdate colorimetric procedure employed by Murphy and Riley (1962). The detection limit was 0.01 mg L^{-1} for each nutrient in runoff water samples. Routine soil and tissue samples were collected immediately before fertilization and immediately after each irrigation or natural rainfall event. Soil samples were analyzed for P by the Bray-1 method and inorganic N by KCl extraction. Tissue samples were analyzed for total N by dry combustion and total P by dry ashing. Three simulated and three natural rainfall events were recorded.

Loading rates of nutrients following runoff initiation were calculated by multiplying average nutrient concentration during each sampling interval [(concentration at time 1 + concentration at time 2) / 2] by the total amount of runoff that passed through the Parshall flume during each specific 5 min sample period. The total nutrient load for each treatment during the first 60 min following runoff initiation was computed by adding the total amount of NO_3-N, NH_4-N, or DRP that were calculated for each 5 min sample period.

Nutrient loads were also calculated for each plot in 5 min intervals from beginning of irrigation or rainfall until 60 min following beginning of irrigation or rainfall to assess the affects of runoff inhibition between treatments. These data were used to determine if differences in time from irrigation or rainfall to runoff between treatments significantly affected the amount of nutrient potentially entering surface waters in a given period after irrigation or rainfall began. Nutrient concentrations for specific times until 60 min following beginning of rainfall were found by entering treatment data from 5-60 min following runoff initiation for each replication into TableCurve 2D 5.0 (SPSS, Chicago, IL), using the Curve-Fit Linear Equation function, and then choosing the best Curve-Fit Equation. Loading rates of nutrients following beginning of irrigation or rainfall were also calculated by multiplying average nutrient concentration during each 5 min interval [(concentration at time 1 + concentration at time 2) / 2] by the total amount of runoff that passed through the Parshall flume during each specific 5 min period. The total nutrient load for each treatment during the first 60 min following beginning of irrigation or rainfall was computed by adding the total amount of NO_3-N, NH_4-N, or DRP that were calculated for each specific 5 min period.

Statistical analysis was performed using SAS version 8.1. Time series analysis was used to determine nutrient runoff as a function of precipitation or irrigation duration for a randomized complete block design. Repeated measures analysis was performed using PROC MIXED with time as the repeated measure treatment. A model for intraplot variance was determined using an auto regressive variance model. All results were tested at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Three simulated and three natural rainfall events were recorded in 2001. All natural rainfall events produced measurable runoff but only one event produced a sufficient amount to collect nutrient concentration samples. Irrigation coefficient of uniformity was 80% for each plot.

Runoff Water Samples

Background levels of nutrients in irrigation water samples were 0.26 mg L^{-1} for NO_3-N, 0.10 mg L^{-1} for NH_4-N, and 0.05 mg L^{-1} for DRP and in natural rainfall samples 0.88 mg L^{-1} for NO_3-N, 0.04 mg L^{-1} for NH_4-N, and 0.05 mg L^{-1} for DRP. Average nitrate-N concentrations in runoff did not exceed 0.41 mg L^{-1} during any of the simulated rainfall events and did not exceed 2.34 mg L^{-1} during the natural rainfall event (Tables 1 and 2). Nitrate-N concentration amounts for both the simulated and natural rainfall events were well under the established NO_3-N drinking water standard of 10 mg L^{-1} set by the US Environmental Protection Agency regardless of treatment and were not significantly different from the background concentrations measured in simulated and natural rainfall water samples. Linde et al. (1994) observed similar results in their study of nutrient transport in runoff from creeping bentgrass and perennial ryegrass maintained as golf course fairways. They found that NO_3-N concentrations and loading rates rarely exceeded those found in the irrigation water under the parameters of their research.

Average ammonium-N concentrations did not exceed 5.80 mg L^{-1} during the simulated rainfall events and did not exceed 0.85 mg L^{-1} during the natural rainfall event (Tables 1 and 2). Ammonium-N concentrations in runoff were significantly greater than the background concentrations measured in simulated and natural rainfall water samples.

Average dissolved reactive phosphorus concentrations did not exceed 7.69 mg L^{-1} during the simulated rainfall events and did not exceed 2.33 mg L^{-1} during the natural rainfall event (Tables 1 and 2). Dissolved reactive phosphorus concentrations in runoff were significantly greater than the background concentrations measured in simulated and natural rainfall water samples.

Eutrophication of surface waters may occur with concentrations of N as low as 1 mg L^{-1} and with concentrations of P as low as 25 μg L^{-1} with entry values of 50 μg L^{-1} P being the upper limit for protection (Walker and Branham, 1992). Background levels of P in both irrigation and natural rainfall samples were 50 μg L^{-1} and the concentrations of N, and more importantly P, in runoff during both the simulated and natural rainfall events exceeded levels that have been shown to cause eutrophication of surface waters regardless of treatment. Further research is needed to develop management strategies that will reduce nutrient concentrations found in surface runoff from highly maintained turfgrass areas.

Total volume of runoff from plots during the 60 min following initiation of runoff were not significantly different between single VFS and multiple VFS of increasing height during both simulated (Table 3) and natural (Table 4) rainfall events.

Nitrate-N, NH_4-N, and DRP concentration levels measured at 5 min intervals for 60 min following runoff initiation for each plot were not statistically different between treatments (Table 5). These results correspond with Cole et al. (1997) where they observed no significant differences in nutrient runoff concentrations due to VFS mowing height.

Time to initiation of runoff was not statistically different between treatments for the simulated rainfall event, but was statistically different between treatments for the natural rainfall events (Table 6). Multiple VFS of increasing height increased time to initiation of runoff by 53% during the natural rainfall events (Table 7).

In both the simulated and natural rainfall studies, total NO_3-N, NH_4-N, and DRP loading rates in surface runoff collected for one hour after runoff initiation were not significantly different between treatments (Table 8) and loading rates calculated in surface runoff for 60 min following beginning of rainfall or irrigation were not significantly different between treatments (Table 9). These results indicated that under the parameters of this study, there were no significant differences in loading rates between single VFS and multiple VFS of increasing height despite the fact that multiple VFS of increasing height increased time to initiation of runoff.

Soil Samples

There were no significant differences between soil samples taken before fertilization and after irrigation for NO_3-N, NH_4-N, or Bray-1 P levels in the soil or thatch layer as a result of simulated rainfall (Table 10). This is likely due to the heavy irrigation application that followed fertilization. The applied fertilizer that became soluble was likely washed away in the surface runoff before it could infiltrate deeply into the soil profile. There were no significant differences between NO_3-N, NH_4-N, and Bray-1 P samples taken before fertilization and after natural rainfall in the soil or thatch layer with the exception of thatch NO_3-N and NH_4-N (Table 11). The P level in the thatch layer increased after natural rainfall but was not statistically significant. The increase of N in the thatch layer after natural rainfall was probably due to the slow rate of precipitation during the natural rainfall events and to the length of time between fertilizer application and precipitation (2-7 d).

Tissue Samples

There were no significant differences between tissue samples taken before fertilization and after irrigation during simulated rainfall for total N (Table 12). There was a significant increase in total P tissue concentration after the simulated rainfall event. This may be due to the solubility of triple superphosphate fertilizer. The plants may have been able to take up the P fertilizer during the simulated event because triple superphosphate fertilizer dissolved quickly due to the heavy irrigation intensity and amount. This may also explain why the plants did not increase uptake of P during the natural rainfall events (Table 13), in which precipitation rates were lower and duration of water applied was shorter than the simulated events. This may also explain why the highest concentration of DRP found in the simulated runoff water samples (7.69 mg L^{-1}) was much higher than the greatest concentration found in the natural rainfall runoff water samples (2.33 mg L^{-1}). Also, time between fertilizer application and precipitation was much longer for the natural rainfall events (2-7 d) when compared to the simulated rainfall events (4 h). Total N tissue concentrations for the natural rainfall events significantly increased following precipitation (Table 13). Total P tissue concentration for the natural rainfall events was not significantly different. The increased level of N found in the tissues is probably due to the slow rate of precipitation that fell during the natural rainfall events and to the length of time between fertilizer application and precipitation (2-7 d).

Fertilizer Fate

A total of 1.45 kg N and 0.73 kg P was applied to each plot before each simulated or natural rainfall event. The amount of applied N recovered in surface water runoff for the first hour following runoff initiation during simulated rainfall events from the single VFS treatment was 2.08% and from the multiple VFS of increasing heights treatment was 1.83% (Table 14). The amount of applied P recovered in surface water runoff for the first hour following runoff initiation during simulated rainfall events from the single VFS treatment was 4.34% and from the multiple VFS of increasing heights was 3.78% (Table 14). There were no significant differences in amount of nutrient loss from applied fertilizer in runoff during the first hour following runoff initiation between single and multiple VFS during simulated rainfall.

The amount of applied N recovered in surface water runoff for the first hour following runoff initiation during the natural rainfall event from the single VFS treatment was 0.26% and from the multiple VFS of increasing heights treatment was 0.25% (Table 14). The amount of applied P recovered in surface water runoff for the first hour following runoff initiation during natural rainfall events from the single VFS treatment was 0.47% and from the multiple VFS of increasing heights treatment was 0.47% (Table 14). There was no significant difference in amount of nutrient loss in runoff from applied fertilizer during the first hour following runoff initiation between single and multiple VFS during natural rainfall. The remaining fertilizer nutrients that could not be accounted for in runoff water, soil, or thatch samples could still be seen on each plot as granules.

SUMMARY

There were no significant differences between single VFS and multiple VFS of increasing height for the reduction of NO_3-N, NH_4-N, and DRP applied as urea and triple superphosphate on bermudagrass golf course fairways. Multiple VFS of increasing height did increase time to initiation of runoff by 53% when compared to single VFS during natural rainfall events, but there were no significant differences in total nutrient load during both simulated and natural rainfall events between the two treatments. There were no significant differences in NO_3-N, NH_4-N, and DRP concentrations found in runoff water between single VFS and multiple VFS of increasing height. Nitrate-N concentrations in runoff did not exceed the US Environmental Protection Agency drinking water standard of 10 mg L^{-1} regardless of treatment. Although percent loss of applied N and P from fertilizer was low, NO_3-N, NH_4-N, and DRP concentrations found in surface water runoff from bermudagrass fairways were higher than those previously found to contribute to eutrophication of surface waters regardless of treatment. Further research is thus needed to develop management strategies that may reduce total runoff volume and nutrient concentrations found in surface water runoff from golf course areas.

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Table 1. Average nutrient concentrations of runoff samples during the three simulated rainfall events in July, August, and September 2001.†

Treatment	Sample time	Nutrient concentrations‡		
		NO_3-N ± SD	NH_4-N ± SD	DRP ± SD
	min	mg L^{-1}		
Single VFS§				
	5	0.20 ± 0.13	0.27 ± 0.25	1.52 ± 0.75
	10	0.29 ± 0.11	1.31 ± 1.00	3.15 ± 2.68
	15	0.32 ± 0.13	3.26 ± 1.71	4.77 ± 2.72
	20	0.35 ± 0.13	4.80 ± 1.42	6.98 ± 1.80
	25	0.31 ± 0.19	5.73 ± 1.50	7.69 ± 1.86
	30	0.34 ± 0.17	5.80 ± 1.48	7.15 ± 1.77
	35	0.36 ± 0.13	5.39 ± 1.15	6.16 ± 1.81
	40	0.38 ± 0.07	5.31 ± 1.06	6.00 ± 1.52
	45	0.36 ± 0.13	5.09 ± 1.00	5.62 ± 1.68
	50	0.40 ± 0.04	4.70 ± 0.90	5.15 ± 1.58
	55	0.40 ± 0.04	4.55 ± 0.98	4.73 ± 1.55
	60	0.38 ± 0.07	4.47 ± 1.24	4.58 ± 1.54
Multiple VFS¶				
	5	0.20 ± 0.13	0.75 ± 1.26	1.92 ± 0.69
	10	0.29 ± 0.13	2.16 ± 2.42	3.43 ± 1.30
	15	0.33 ± 0.14	3.95 ± 2.46	6.08 ± 2.06
	20	0.36 ± 0.18	4.88 ± 2.20	6.97 ± 2.25
	25	0.36 ± 0.18	5.22 ± 2.08	6.91 ± 1.66
	30	0.41 ± 0.11	5.39 ± 2.24	6.98 ± 1.55
	35	0.40 ± 0.10	5.03 ± 1.67	6.27 ± 1.70
	40	0.36 ± 0.16	4.87 ± 1.68	6.05 ± 1.64
	45	0.41 ± 0.10	4.49 ± 1.48	5.24 ± 1.42
	50	0.38 ± 0.14	4.24 ± 1.57	5.00 ± 1.46
	55	0.37 ± 0.13	3.93 ± 1.47	4.49 ± 1.28
	60	0.41 ± 0.09	3.77 ± 1.50	3.88 ± 1.10

† No significant sampling date x treatment interaction.

‡ n = 9 for each sample time (3 replications x 3 sampling dates).

§ Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

¶ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

Table 2. Average nutrient concentrations of runoff samples during the natural rainfall event in September 2001.†

Treatment	Sample time	Nutrient concentrations		
		NO_3-N ± SD	NH_4-N ± SD	DRP ± SD
	min	mg L^{-1}		
Single VFS‡				
	5	0.99 ± 0.24	0.23 ± 0.19	0.99 ± 0.12
	10	1.20 ± 0.18	0.19 ± 0.33	1.29 ± 0.20
	15	1.46 ± 0.34	0.22 ± 0.38	1.52 ± 0.14
	20	1.26 ± 0.18	0.34 ± 0.30	1.96 ± 0.23
	25	1.22 ± 0.24	0.40 ± 0.35	1.89 ± 0.23
	30	1.14 ± 0.17	0.50 ± 0.26	2.03 ± 0.14
	35	1.42 ± 0.10	0.48 ± 0.44	1.99 ± 0.36
	40	1.45 ± 0.51	0.50 ± 0.29	2.06 ± 0.31
	45	1.59 ± 0.57	0.67 ± 0.16	2.13 ± 0.31
	50	2.34 ± 1.22	0.85 ± 1.21	1.96 ± 0.25
	55	1.01 ± 0.09	0.45 ± 0.04	1.83 ± 0.42
	60	1.11 ± 0.08	0.64 ± 0.01	2.02 ± 0.29
Multiple VFS§				
	5	0.96 ± 0.34	0.32 ± 0.22	1.31 ± 0.40
	10	1.66 ± 0.34	0.30 ± 0.27	1.60 ± 0.17
	15	1.45 ± 0.58	0.38 ± 0.34	1.76 ± 0.19
	20	1.53 ± 0.36	0.21 ± 0.36	2.11 ± 0.43
	25	1.39 ± 0.08	0.31 ± 0.33	2.15 ± 0.20
	30	1.65 ± 0.40	0.65 ± 0.20	2.26 ± 0.17
	35	1.53 ± 0.11	0.54 ± 0.20	2.33 ± 0.03
	40	1.01 ± 0.33	0.43 ± 0.19	2.19 ± 0.10
	45	1.44 ± 0.33	0.41 ± 0.19	2.22 ± 0.10
	50	0.96 ± 0.33	0.39 ± 0.20	2.21 ± 0.10
	55	1.00 ± 0.33	0.41 ± 0.20	2.17 ± 0.10
	60	0.92 ± 0.33	0.50 ± 0.19	2.16 ± 0.10

† n = 3 replications for each sample time.

‡ Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

§ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

Table 3. Total amount of runoff from plots during each specific 5 min sample period and cumulative total for the 60 min sample period during the three simulated rainfall events in July, August, and September 2001.†

Treatment	Sample time	July	August	September
	min	L ± SD		
Single VFS‡				
	5	140.94 ± 82.54	98.42 ± 83.59	85.61 ± 45.08
	10	250.08 ± 138.18	212.29 ± 38.06	326.80 ± 123.40
	15	353.36 ± 181.78	452.22 ± 21.65	482.06 ± 163.89
	20	388.94 ± 218.17	550.26 ± 13.88	549.63 ± 112.88
	25	396.70 ± 195.04	598.90 ± 65.44	613.41 ± 105.53
	30	425.41 ± 222.33	621.36 ± 53.01	636.63 ± 114.16
	35	458.78 ± 235.25	630.95 ± 77.91	641.55 ± 111.02
	40	475.63 ± 262.33	634.86 ± 43.09	638.15 ± 128.48
	45	467.30 ± 212.95	677.95 ± 79.31	614.42 ± 104.54
	50	420.80 ± 286.87	636.63 ± 44.73	650.45 ± 109.92
	55	404.40 ± 356.79	686.47 ± 87.67	628.05 ± 93.14
	60	372.54 ± 320.31	709.50 ± 98.05	623.89 ± 104.21
	Cumulative total§	4554.88 ± 226.04	6509.80 ± 58.87	6490.65 ± 109.69
Multiple VFS¶				
	5	76.53 ± 45.99	67.19 ± 72.07	79.87 ± 47.60
	10	195.39 ± 114.82	202.52 ± 158.67	260.05 ± 79.26
	15	238.10 ± 104.44	361.82 ± 121.33	435.12 ± 88.53
	20	323.08 ± 97.67	446.92 ± 63.66	516.95 ± 36.08
	25	342.44 ± 129.85	497.84 ± 56.72	558.65 ± 62.67
	30	378.60 ± 86.68	508.50 ± 25.79	639.03 ± 126.80
	35	380.74 ± 100.32	546.29 ± 15.85	658.71 ± 188.09
	40	384.02 ± 73.65	541.05 ± 22.54	619.28 ± 64.69
	45	389.57 ± 83.84	541.11 ± 11.65	657.58 ± 139.97
	50	397.40 ± 105.33	524.46 ± 42.71	626.28 ± 65.30
	55	365.85 ± 62.68	521.37 ± 70.52	646.22 ± 148.92
	60	315.51 ± 160.83	516.76 ± 17.33	634.11 ± 76.40
	Cumulative total§	3787.23 ± 97.18	5275.83 ± 56.57	6331.85 ± 93.69

† n = 3 replications for each sample time.

‡ Single VFS (vegetative filter strips) were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

§ Cumulative total is the total amount of runoff during the first hour after runoff initiation.

¶ Multiple VFS consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

Table 4. Total amount of runoff from plots during each specific 5 min sample period and cumulative total for the 60 min sample period during the natural rainfall event in September 2001.†

Treatment	Sample time	September
	min	L ± SD
Single VFS‡		
	5	687.67 ± 78.64
	10	850.00 ± 227.12
	15	423.20 ± 205.35
	20	197.47 ± 119.26
	25	106.75 ± 88.48
	30	67.71 ± 63.67
	35	48.97 ± 47.47
	40	38.43 ± 36.90
	45	32.57 ± 32.35
	50	27.76 ± 27.27
	55	19.62 ± 21.72
	60	18.80 ± 19.03
	Cumulative total§	2518.84 ± 80.61
Multiple VFS¶		
	5	1028.92 ± 573.86
	10	866.84 ± 409.83
	15	270.84 ± 88.12
	20	97.03 ± 55.99
	25	27.33 ± 38.04
	30	17.00 ± 29.37
	35	7.20 ± 12.45
	40	1.58 ± 2.73
	45	0.01 ± 0.02
	50	0.01 ± 0.02
	55	0.01 ± 0.02
	60	0.01 ± 0.02
	Cumulative total§	2316.78 ± 100.87

† n = 3 replications for each sample time

‡ Single VFS (vegetative filter strips) were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

§ Cumulative total is the total amount of runoff during the first hour after runoff initiation.

¶ Multiple VFS consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

Table 5. Tests for differences in nutrient concentrations at 5 min intervals for 60 min following runoff initiation between single vegetative filter strip (VFS)† and multiple VFS‡ during simulated and natural rainfall events.

			Type 3 tests of fixed effects			
Event	Dependent variable	Effect	Numerator df	Denominator df	F value	Pr > F
Simulated						
	NO_3-N					
		Trt	1	46.50	1.36	0.25
		Sampletime	11	162.00	8.21	<0.01
		Trt x Sampletime	11	162.00	0.71	0.73
	NH_4-N					
		Trt	1	9.81	0.00	0.97
		Sampletime	11	174.00	30.19	<0.01
		Trt x Sampletime	11	174.00	2.31	0.01
	DRP§					
		Trt	1	15.80	0.00	0.99
		Sampletime	11	170.00	22.62	<0.01
		Trt x Sampletime	11	170.00	1.50	0.14
Natural						
	NO_3-N					
		Trt	1	6.67	0.41	0.54
		Sampletime	11	26.70	1.95	0.08
		Trt x Sampletime	11	26.70	2.39	0.03
	NH_4-N					
		Trt	1	10.10	0.18	0.68
		Sampletime	11	26.30	0.93	0.53
		Trt x Sampletime	11	26.30	0.55	0.85
	DRP§					
		Trt	1	4.55	2.32	0.19
		Sampletime	11	27.40	7.48	<0.01
		Trt x Sampletime	11	27.40	0.30	0.98

† Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

‡ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

§ DRP = dissolved reactive phosphorus.

Table 6. Tests for differences between single vegetative filter strips (VFS)† and multiple VFS‡ for time to initiation of runoff during simulated and natural rainfall events.§

Type 3 tests of fixed effects					
Event	Effect	Numerator df	Denominator df	F value	Pr > F
Simulated					
	Trt	1	14	2.20	0.1600
Natural					
	Trt	1	14	16.39	0.0012

† Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

‡ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

§ n = 9 for both simulated and natural events (3 replications x 3 sampling dates).

Table 7. Mean time to initiation of runoff between single vegetative filter strips (VFS)† and multiple VFS‡ during simulated and natural rainfall events. §

Event	Treatment	Mean	SE
Simulated		min	
	Single VFS	12.67	2.67
	Multiple VFS	15.56	2.67
Natural			
	Single VFS	15.22	2.95
	Multiple VFS	23.22*	2.95

* Significant at the 0.05 probability level.

† Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

‡ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation

§ n = 9 for both simulated and natural events (3 replications x 3 sampling dates).

Table 8. Tests for differences in total nutrient loading between single vegetative filter strips (VFS)† and multiple VFS‡ for 60 min following initiation of runoff during simulated and natural rainfall events.§

			Type 3 tests of fixed effects			
Event	Dependent variable	Effect	Numerator df	Denominator df	F value	Pr > F
Simulated						
	NO_3-N					
		Trt	1	23.10	0.29	0.59
		Sampletime	11	168.00	14.88	<0.01
		Trt x Sampletime	11	168.00	0.75	0.69
	NH_4-N					
		Trt	1	6.77	0.45	0.52
		Sampletime	11	175.00	29.18	<0.01
		Trt x Sampletime	11	175.00	1.36	0.19
	DRP¶					
		Trt	1	13.60	0.78	0.39
		Sampletime	11	174.00	30.29	<0.01
		Trt x Sampletime	11	174.00	1.54	0.12
Natural						
	NO_3-N					
		Trt	1	2.23	1.49	0.33
		Sampletime	11	27.10	12.88	<0.01
		Trt x Sampletime	11	27.10	2.58	0.02
	NH_4-N					
		Trt	1	12.50	0.01	0.93
		Sampletime	11	24.20	2.26	0.05
		Trt x Sampletime	11	24.20	0.41	0.94
	DRP¶					
		Trt	1	2.49	1.04	0.40
		Sampletime	11	26.70	9.71	<0.01
		Trt x Sampletime	11	26.70	2.23	0.04

† Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

‡ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

§ n = 3 replications for natural event and n = 9 for simulated events (3 replications x 3 sampling dates).

¶ DRP = dissolved reactive phosphorus.

Table 9. Tests for differences in total loading between single vegetative filter strips (VFS)† and multiple VFS‡ for 60 min following beginning of irrigation or rainfall during simulated and natural rainfall events.§

Event	Dependent variable	Effect	Type 3 tests of fixed effects: Numerator df	Denominator df	F value	Pr > F
Simulated						
	NO_3-N	Trt	1	11.80	0.10	0.76
		Sampletime	16	167.00	14.84	<0.01
		Trt x Sampletime	14	167.00	1.17	0.30
	NH_4-N	Trt	1	7.62	0.45	0.52
		Sampletime	16	170.00	15.90	<0.01
		Trt x Sampletime	14	170.00	0.45	0.95
	DRP¶	Trt	1	13.40	0.36	0.56
		Sampletime	16	169.00	17.28	<0.01
		Trt x Sampletime	14	168.00	0.58	0.88
Natural						
	NO_3-N	Trt	1	6.99	0.02	0.90
		Sampletime	11	28.70	7.76	<0.01
		Trt x Sampletime	11	28.70	0.30	0.98
	NH_4-N	Trt	1	4.64	0.04	0.84
		Sampletime	11	30.40	8.60	<0.01
		Trt x Sampletime	11	30.40	1.68	0.13
	DRP¶	Trt	1	5.28	0.02	0.91
		Sampletime	11	29.00	10.88	<0.01
		Trt x Sampletime	11	29.00	0.97	0.49

† Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

‡ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

§ n = 3 replications for the natural event and n = 9 for the simulated events (3 replications x 3 sampling dates).

¶ DRP = dissolved reactive phosphorus.

Table 10. Soil samples before fertilization and after simulated rainfall: all simulated events. †

Type	Taken	NO_3-N ± SD	NH_4-N ± SD	Bray-1 P ± SD
			mg kg^{-1}	
Soil				
	Before	4.44 ± 1.53	4.73 ± 2.22	18.33 ± 4.65
	After	4.76 ± 1.86	5.34 ± 1.84	20.33 ± 4.63
Thatch				
	Before	6.88 ± 2.81	10.86 ± 3.56	65.06 ± 6.86
	After	6.19 ± 1.68	11.43 ± 2.43	64.17 ± 10.21

† n = 18 for soil and thatch before and after samples.

Table 11. Soil samples before fertilization and after rainfall: all natural events.†

Type	Taken	NO_3-N ± SD	NH_4-N ± SD	Bray-1 P ± SD
		mg kg^{-1}		
Soil				
	Before	3.95 ± 1.61	3.63 ± 0.55	18.33 ± 4.23
	After	3.23 ± 1.11	3.77 ± 0.77	22.83 ± 7.08
Thatch				
	Before	5.87 ± 1.48	11.48 ± 1.43	62.83 ± 9.37
	After	10.40 ± 2.85*	14.27 ± 1.19*	71.17 ± 8.91

* Significant at the 0.05 probability level.
† n = 18 for soil and thatch before and after samples.

Table 12. Tissue samples before fertilization and after precipitation event: simulated rainfall.†

Type	Taken	N ± SD	P ± SD
		g kg^{-1}	
Tissue			
	Before	31.15 ± 6.65	3.38 ± 0.45
	After	31.54 ± 5.94	4.55 ± 1.12 *

* Significant at the 0.05 probability level.

† n = 18 for before and after samples.

Table 13. Tissue samples before fertilization and after precipitation event: natural rainfall. †

Type	Taken	N ± SD	P ± SD
		g kg^{-1}	
Tissue			
	Before	29.93 ± 5.57	3.84 ± 0.51
	After	42.35 ± 2.41 *	3.88 ± 0.23

* Significant at the 0.05 probability level.

† n = 18 for before and after samples.

Table 14. Amount of total applied fertilizer recovered in surface runoff in dissolved forms from single vegetative filter strips (VFS) † and multiple VFS‡ after initiation of runoff during simulated and natural rainfall events.§

Event	Treatment	Total N ± SD	Total P ± SD
		kg	
Simulated			
	Single VFS	0.0302 ± 0.0120	0.0317 ± 0.0160
	Multiple VFS	0.0265 ± 0.0150	0.0276 ± 0.0140
Natural			
	Single VFS	0.0037 ± 0.0006	0.0034 ± 0.0007
	Multiple VFS	0.0036 ± 0.0008	0.0034 ± 0.0007

† Single vegetative filter strips were 12.2 x 5.5 m of bermudagrass mowed at 5.1 cm.

‡ Multiple vegetative filter strips consisted of three adjacent 12.2 x 1.8 m bermudagrass strips mowed at increasing heights (2.5, 3.8, and 5.1 cm) with decreasing elevation.

§ n = 3 replications for the natural event and n = 9 for the simulated events (3 replications x 3 sampling dates).

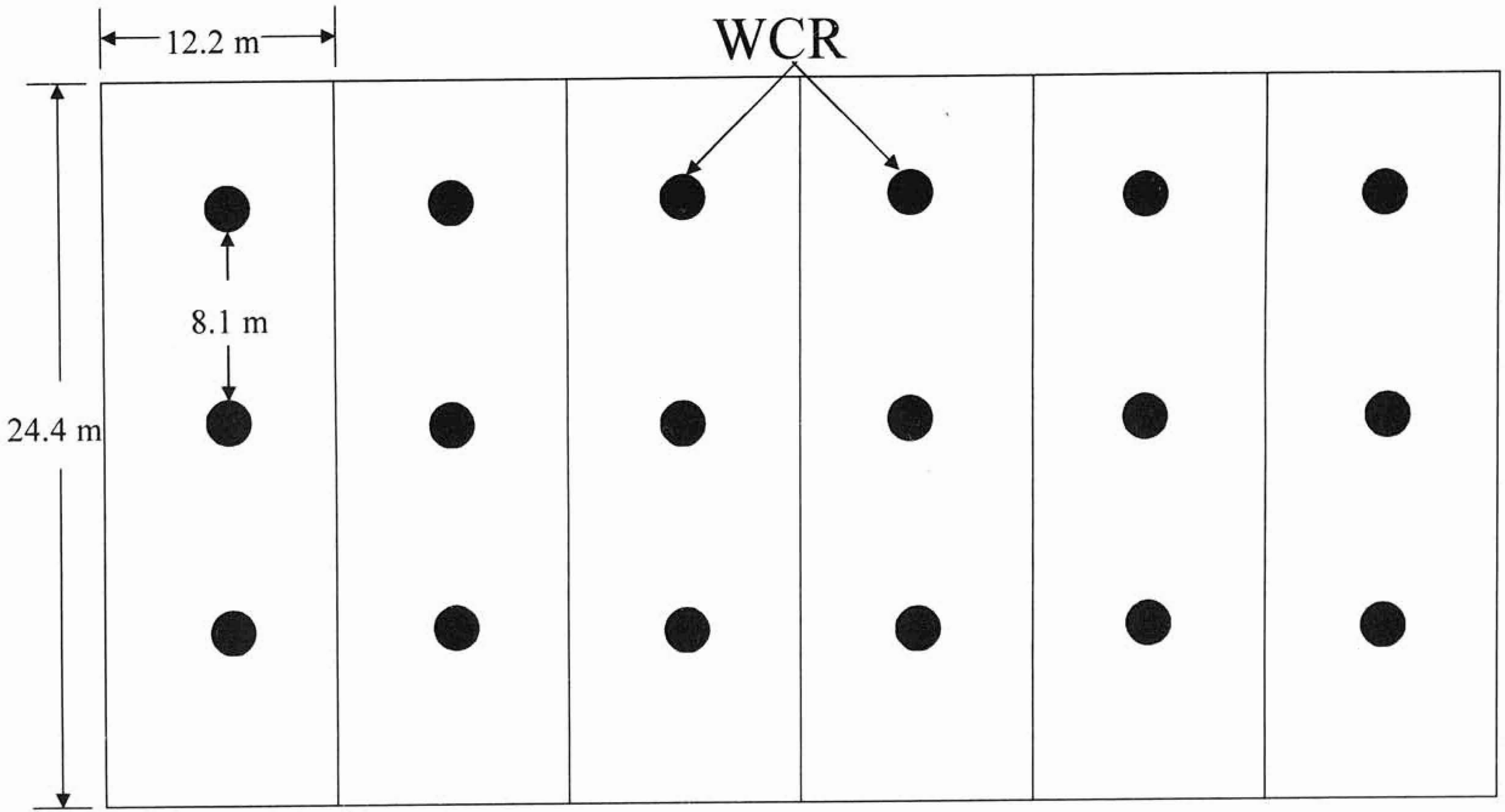

Fig. 1. Schematic of plots and location of water content reflectometers (WCR).

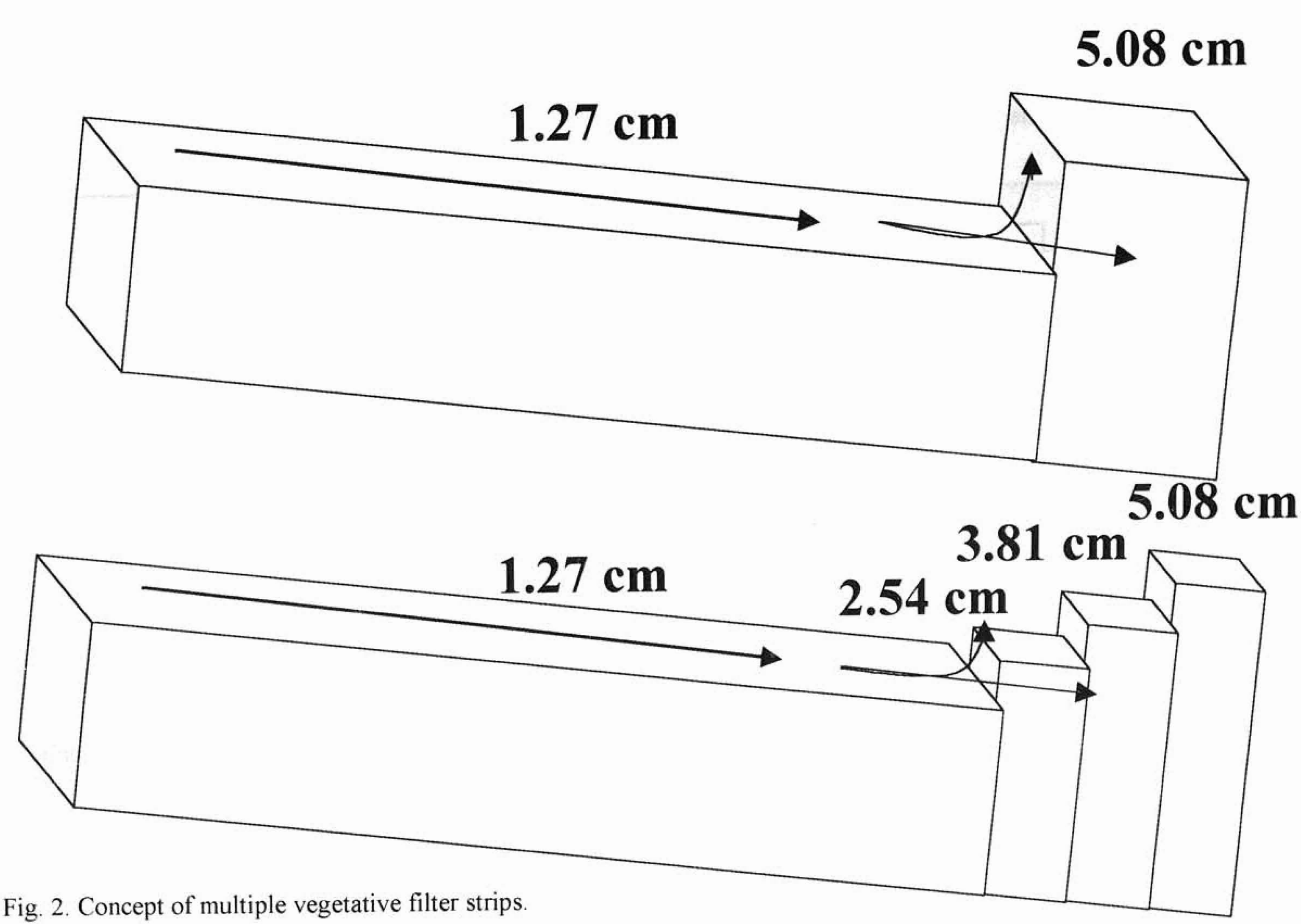

Fig. 2. Concept of multiple vegetative filter strips.

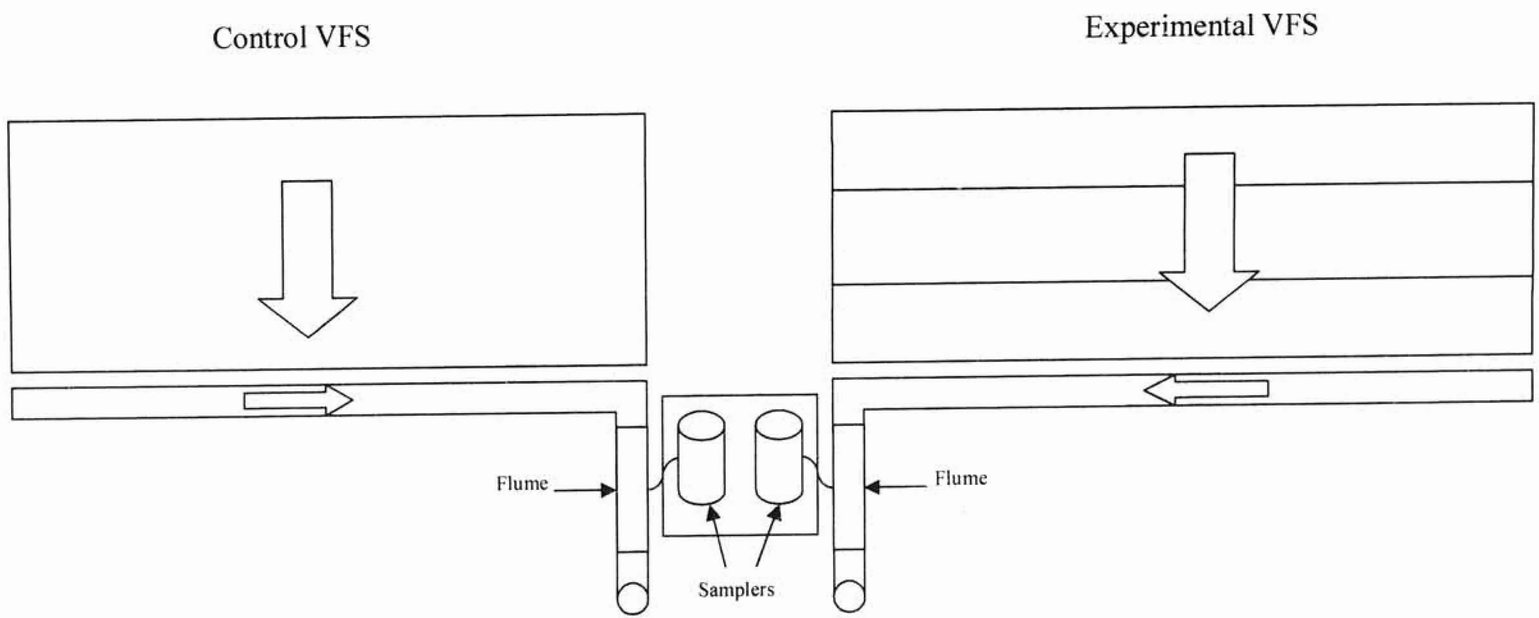

Fig. 3. Schematic of troughs, flumes and samplers (not to scale).

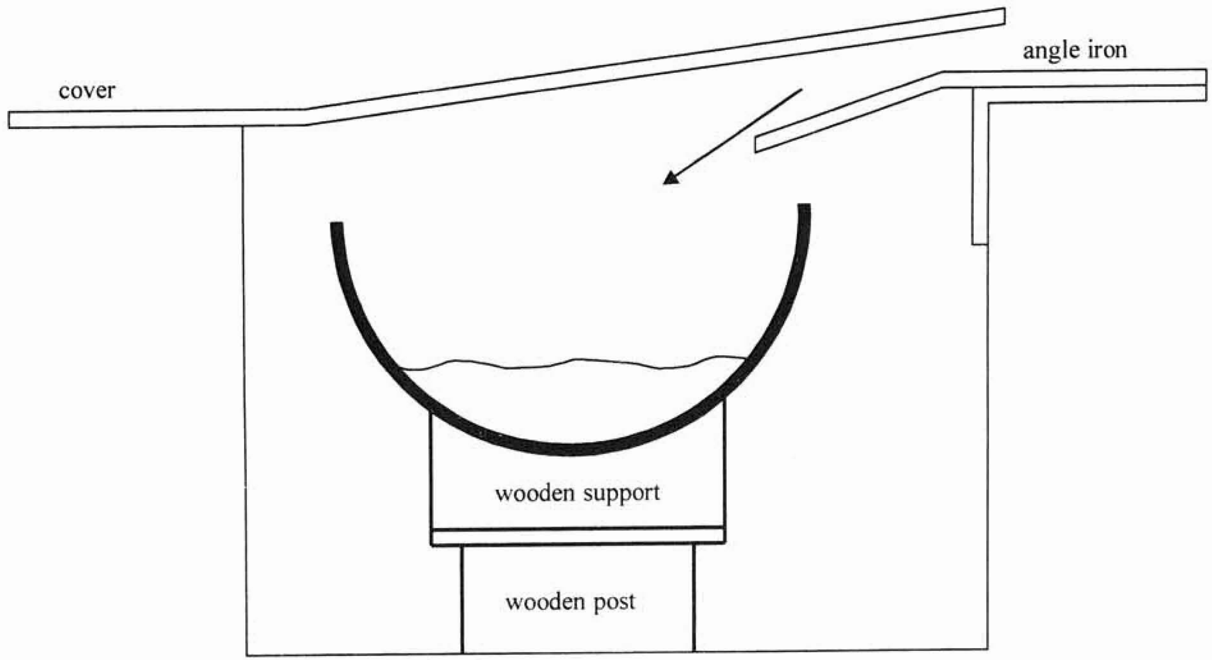

Fig. 4. Schematic of cover, angle iron, trough, wooden support and post (not to scale).

VITA

Justin Quetone Moss 2

Candidate for the Degree of

Master of Science

Thesis: REDUCING NUTRIENT RUNOFF FROM GOLF COURSE FAIRWAYS USING MULTIPLE VEGETATIVE FILTER STRIPS

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Personal Data: Born in Claremore, Oklahoma, on July 30, 1975, the son of Harold G. and Laura L. Moss.

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