A Comparison of the Effects of Alternative Turfgrass Management Practices on Nutrient Loads in Runoff and Percolation

Final Report

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Executive Summary

There are over three-quarters of a million acres of pervious urban land in Virginia's portion of the Chesapeake Bay Basin (Gutierrez-Magness et al., 1997), much of it home lawns. The amount of fertilizer used on these lawns is unknown. Nevertheless, just as nutrient management can reduce the export of nitrogen and phosphorus from agricultural land, it is possible that a substantial reduction in the export of nutrients from home lawns could be obtained by adjusting the rate and timing of fertilizer applications to turfgrass.

Scope of Work

The purpose of this project was to use computer simulation to study the how the rate and timing of fertilizer applications to turfgrass affect the export of nutrients from home lawns. The primary emphasis of the study was to compare the effects of the fertilizer schedules on nitrogen losses in runoff and percolation. It was assumed that erosion losses from turfgrass would be minimal, and the primary paths for nutrient export would be in runoff and percolation. It also was assumed that phosphorus losses would be negligible unless the concentration of phosphorus in the soil was high. This indeed turned out to be case. Because phosphorus losses were in general quite low, the effect of the rate and timing of the fertilizer application on phosphorus losses was not analyzed. Additional simulations were performed, however, to determine the effect of soil phosphorus concentration on phosphorus losses in runoff.

The computer model, EPIC (Environmental Policy Integrated Climate), was used to simulate the growth of turfgrass under different fertilization schedules. Two schedules, Lawn Service I and II, represented the rate and timing of nutrient applications typically used by lawn care service companies. The Four-Step schedule represented the recommendations of lawn care product manufacturers. Five schedules, Extension Service I -V, represented the recommendations of the Virginia Cooperative Extension Service.

Both cool-season grass and warm-season grass were represented on a range of soils. Simulations using cool-season grass were represented using soils and meteorological conditions in the Washington metropolitan region in northern Virginia, while simulations using warm-season grass were represented using soils and conditions in the Richmond area in southern Virginia. Three soils were simulated in each area, representing soils from hydrological groups A, B, and C. Extension Service I, II, and III were used only on cool-season grass, while Extension Service IV and V were used on warm-season grass. The other schedules were simulated on both grass types. The effects of management practices like watering the lawn, and removing or returning lawn clippings, were also examined.

Simulation Results

The results of these simulations indicate that although the potential exists for substantial nitrogen losses from turfgrass on home lawns, it is possible to minimize nitrogen losses by controlling the rate and timing of fertilizer application, regardless of the type of grass or the type of soil the grass is on.

Monthly Nitrogen Fertilization Rates (lbs N/1000 ft^2)

	LS I	LS II	FS	ES I	ES II	ES III	ES IV	ES V
JAN								
FEB	0.75	0.70						
MAR			1.00					
APR	0.75	0.75					1.0	1.0
MAY			0.80				1.0	1.0
JUN	0.75	0.30					1.0	1.0
JUL			0.90					
AUG	0.75	0.30						1.0
SEP		1.10		1.00	1.00	1.50		
OCT	1.00			1.00	1.00	1.50		
NOV		1.40	0.90		1.00			
DEC	1.00			1.00		1.50		

In general, nitrogen losses were higher on warm-season grass than on cool-season grass. The higher losses from warm-season grass stem from its shorter growing season and its more limited capacity to take up nitrogen during the growing season. Simulated average annual nitrogen losses were as high as 25 lb/ac on cool-season grass and 78 lb/ac on warm-season grass. Losses could be reduced to 5-10 lb/ac annually by using the Extension Service II schedule on cool-season grass and the Extension Service IV on warm-season grass.

The Principle Causes of Nitrogen Losses

The principle cause of nitrogen losses, at least on soils from hydrologic groups A and B where little runoff occurs, is the vulnerability of soil nitrate to leaching in the winter and early spring before the growing season begins. Winter and early spring is the period of the year with the greatest percolation. It is also the period of the year when the demand for nitrate by the turfgrass is at a minimum. The higher the average level of nitrate in the soil during this period, the greater the nitrogen losses in percolation.

Nitrogen losses in percolation also increase whenever the supply of nitrogen in the soil is greater than the demand. The simulation results suggest that the demand for nitrogen by warm-season grass is limited, and it is possible to supply more nitrogen in fertilizer than the grass needs, especially if clippings are returned to the turf, thus recycling some of the nitrogen used by the grass. While it is more difficult to over-fertilize cool-season grass, returning the clippings to the lawn can lead to increased losses unless the amount of fertilizer applied is also reduced.

On soils from hydrologic groups A and B, the quantity of runoff is small, and nitrogen losses in runoff are small, compared to losses in percolation. On hydrologic group C soils, however, nitrogen losses in runoff tend to be equal or greater than the losses in percolation. Significant nitrogen losses in runoff tend to occur just after nitrogen fertilizer is applied to the turf.

Effects of Fertilizer Schedules

The effects of fertilizer schedules on nitrogen losses are remarkably consistent across management practices and soil types. For cool-season grass, the Extension Service II had the lowest losses, regardless of management practices or soil type, for all simulations except one. The nitrogen losses from Extension Service I were higher but comparable in size to those for Extension Service II. Lawn Service I and II, and Extension Service III had the highest losses. Losses from the Four-Step schedule fell between these two groups. For warm-season grass, the Extension Service IV schedule produces the lowest nitrogen losses for every management scenario and every soil type. The lawn service schedules produce the largest losses. Losses for the Extension V and Four-Step schedules fall between the losses from the lawn service schedules and Extension Service IV.

Rate is the primary factor in determining nitrogen losses. Timing, however, also has an effect. Losses from Extension Service II are consistently several pounds less than those from Extension Service I. These two schedules differ only in the timing of their last fertilizer application.

Effects of Management Practices

Irrigating turf does lead to greater percolation and greater nitrogen losses in percolation, but the increase in losses caused by percolation is small for most soils and most fertilization schedules. The increase in total nitrogen losses was less than 10% in almost all scenarios.

Returning the clippings to the lawn more dramatically increases nitrogen losses. For cool-season grass, the increase in losses ranges from 27% to 80%. The increase in losses on warm-season grass is over 100% on some soils for some fertilization schedules.

Suggestions For Reducing Nitrogen Losses From Turfgrass

The results from these simulations suggest several steps could be taken to reduce nitrogen losses from turfgrass. The following suggestions could be implemented without radically changing current turfgrass management practices:

- For cool-season grass, minimize fertilizer applications that occur in late fall, winter, or early spring while the grass is not removing nitrogen from the soil.
- Lawn service companies could reduce application rates on cool-season grass.
- On warm-season grass, the rate and timing of nitrogen application should be adjusted to take into account the shorter growing season and more limited nitrogen uptake of warm-

season grass.
- Nitrogen application rates should be reduced on all fertilizer schedules if clippings are returned to the lawn.

If these measure are taken, the use of fertilizer on home lawns does not have to lead to excess nutrients reaching ground water and surface water where they can cause environmental problems. The proper rate and timing of nitrogen fertilizer application can minimize the potential impacts of the use of fertilizer on home lawns.

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Introduction

Nutrient reduction is the key to the strategy to restore Chesapeake Bay. Virginia, along with Maryland, Pennsylvania, and the District of Columbia, have agreed to reduce controllable nitrogen and phosphorus loads to the Chesapeake Bay by 40% from their 1985 levels. Efforts have been made to reduce nutrient loads from waste water treatment plants and other point sources, as well as to reduce nutrient loads in runoff and groundwater from agricultural land.

One potentially large source of nutrients is the export of nutrients from lawns. Home lawns constitute a sizable portion of the land use in the Chesapeake Bay Basin. There are over three-quarters of a million acres of pervious urban land in Virginia's portion of the Chesapeake Bay Basin (Gutierrez-Magness et al., 1997), much of it home lawns. The amount of fertilizer used on these lawns is unknown. Nevertheless, just as nutrient management can reduce the export of nitrogen and phosphorus from agricultural land, it is possible that a substantial reduction in the export of nutrients from home lawns could be obtained by adjusting the rate and timing of fertilizer applications to turfgrass.

The purpose of this project was to use computer simulation to study the how the rate and timing of fertilizer applications to turfgrass affect the export of nutrients from home lawns. The computer model, EPIC (Environmental Policy Integrated Climate--formerly, Erosion Productivity Impact Calculator), was used to simulate the growth of turfgrass under different fertilization schedules. These schedules represent the rate and timing of nutrient applications typically used by lawn care service companies, or recommended by lawn care product manufacturers or by the Virginia Cooperative Extension Service. Both cool-season grass and warm-season grass were represented on a range of soils. Simulations using cool-season grass were represented using soils and meteorological conditions in the Washington metropolitan region in northern Virginia, while simulations using warm-season grass were represented using soils and conditions in the Richmond area in southern Virginia. The effects of management practices like watering the lawn, and removing or returning lawn clippings, were also examined.

The primary emphasis of the study was to compare the effects of the fertilizer schedules on nitrogen losses in runoff and percolation. It was assumed that erosion losses from turfgrass would be minimal, and the primary paths for nutrient export would be in runoff and percolation. It also was assumed that phosphorus losses would be negligible unless the concentration of phosphorus in the soil was high. This indeed turned out to be case. Because phosphorus losses were in general quite low, the effect of the rate and timing of the fertilizer application on phosphorus losses was not analyzed. Additional simulations were performed, however, to determine the effect of soil phosphorus concentration on phosphorus losses in runoff.

Before turning to a more detailed description of the simulations and an analysis of their results, it will be helpful to briefly discuss the features of EPIC and the relation between a computer simulation study of turfgrass growth, like this one, and other research on nutrient losses from turfgrass.

The Role of Computer Simulation in Research on Nutrient Losses From Turfgrass

The EPIC model. EPIC was developed by the Agricultural Research Service (ARS) of the U. S. Department of Agriculture. It a field-scale model, working on a daily time-step. It simulates crop growth, the hydrologic and nutrient cycles, and changes in the soil profile. A simulation in EPIC is specified by (1) meteorological data, such as daily precipitation and temperature; (2) the properties of the soil profile, such as the number of soil layers, soil texture, and concentration of organic nitrogen and labile phosphorus in each layer; (3) properties of the crops grown, such as the nitrogen or phosphorus content during the phases of the growing season; and (4) schedule of management operations such as planting and harvesting dates, the rate and timing of fertilizer applications, and tillage operations. Specific features for these simulations are discussed in the next section.

EPIC does not require calibration. It incorporates established methods, such as the curve number procedure for estimating runoff, or draws on literature values to develop relationships between variables. The credibility of EPIC rests not only on the use of established methods and relationships supported by the literature, but on the fact that EPIC maintains a strict accounting of the water, nitrogen, and phosphorus balances. All of the precipitation that is input into the model is accounted for in evapotranspiration, runoff, percolation, and the change in the water content of the soil profile. All of the nitrogen that is applied in fertilizer is accounted for in plant uptake and harvesting, changes in soil storage, or nitrogen losses in runoff, erosion, percolation, denitrification, or volatilization. A detailed account of the structure of the EPIC model can be found in Williams, 1994.

Research on nutrient losses from turfgrass. There are two good sources which review the literature on nitrogen losses from turfgrass. Petrovic (1990) provides a literature review of research on nitrogen losses in runoff and percolation, as well as other aspects of the fate, transport, and transformation of nitrogen in fertilizer applied to turfgrass. Groover et al. (1997), in a report prepared for the Nutrient Subcommittee of the Chesapeake Bay Program, updates Petrovic's literature survey and provides additional details about the spectrum of research on nitrogen losses from turfgrass. The following points emerge from the research:

- The concentration of nitrate nitrogen in percolating soil water rarely exceeds the limit of 10 mg/l set to protect infants against methemoglobinemia or "blue baby syndrome." Generally, observed nitrogen concentrations over a wide range of soil types and fertilizations rates range from 0-3 mg/l and are frequently less than 1 mg/l.

- Few storm events produce runoff on turfgrass. The nitrogen concentrations in runoff usually do not exceed the drinking water standard of 10 mg/l. Most reported concentrations of nitrate nitrogen in runoff are in the range of 1-5 mg/l.

It should be noted that most researchers seemed concerned about whether the transport of nitrogen posed a threat to drinking water supplies. The concentration of nitrogen in runoff and percolation can be less than 10 mg/l, however, and still lead to significant off-field nitrogen transport. The edge-of-field nitrogen transport can exceed 10 lb/ac/yr if the average concentration of nitrogen in percolate is 3 mg/l and annual percolation is 15 inches, if the concentration is 2 mg/l and the annual percolation is little over 20 inches.

The use of computer modeling in estimating nutrient losses from turfgrass. Computer modeling can supplement empirical research by providing a uniform, consistent, and cost-effective framework to make quantitative estimates of nutrient losses over a wide range of conditions. A computer model can look at look-term effects and long-term averages, thus taking into account the inherent variability in weather, whereas most field experiments run at most for one or two years. A computer model applies a consistent set of assumptions to calculate nitrogen losses on different soils or under different management scenarios. The results can be used to compare the relative effects of soils or management practices on nutrient losses.

The results of these computer simulations are offered in this spirit. They cannot take the place of field studies or empirical investigations, but they can provide a framework for identifying the factors which affect nutrient losses from lawns, and to compare the relative effects of fertilization schedules on nutrient losses under a variety of conditions.

Description of Computer Simulation Scenarios, Data Sources, and Simulation Output

The purpose of these computer simulations was to determine the effect of the rate and timing of fertilizer applications on nutrient losses in runoff and percolation from home lawns. Simulated nutrient losses from different fertilization schedules under different scenarios were compared to determine how nutrient losses from different schedules are affected by other factors such as the type of grass grown, soil type, whether the clippings are removed or returned to the lawn, and whether the lawn is irrigated.

These simulations represent lawns in two distinct locations: the metropolitan Washington region in northern Virginia and the Richmond metropolitan region in southern Virginia. Cool-season grasses are grown in northern Virginia. Both warm-season grasses and cool-season grasses are grown in the Richmond area, but this study will concern itself primarily with the growth of warm-season grasses in southern Virginia. For each region three soils were selected representing excessively-drained soils (hydrologic group A), well-drained soils (hydrologic group B), and more moderately well-drained soils (hydrologic group C). Weather is not explicitly a factor examined for its effects on nutrient losses from turf grass.

Three different management scenarios were represented: (1) clippings removed, with no irrigation; (2) clippings removed, with irrigation; and (3) clippings returned, with irrigation. Each computer simulation scenario can thus be characterized by the following factors:

1. weather
2. grass type
3. soil type
4. irrigation
5. clippings management
6. fertilization schedule

The sources of data and general characterization of weather, soil, grass type, and fertilizer schedules will be discussed below. Clippings management and irrigation will be discussed in the sections explicitly dealing with their effects.

Weather

Weather, of course, drives the hydrologic cycle and the growth of plants. EPIC operates on a daily time-step and requires daily weather data: precipitation, maximum temperature, minimum temperature, solar radiation, average wind speed and average relative humidity. Daily values for some or all of these parameters can be read from an input file, or EPIC can generate synthetic weather data, based on summary statistics calculated for selected weather stations around the country. These summary statistics are supplied with the EPIC model. In these simulations, actual weather records were used for precipitation, maximum temperature, and minimum temperature; the other required values were generated by EPIC.

Sources of Weather Data. Of the daily meteorological values generated by EPIC, only solar radiation is actually used by the program in these simulations. The only summary statistic used to generate it is monthly mean solar radiation. Summary statistics from Manassas. VA, were used in the northern Virginia simulations and summary statistics from Richmond were used in the southern Virginia simulations.

Weather records were obtained from the National Climatic Data Center's Summary of the Day database. For the northern Virginia scenarios, twenty-five years of precipitation and temperature data from National Airport for the period 1970-1994 were used. The southern Virginia scenarios use weather data from Richmond International Airport (Byrd Field) for the same period.

Soils

EPIC requires a wide range of soil properties for each soil layer represented in the model. Many of these soil properties, such as the percentage of sand, silt, clay, and organic matter in a soil layer, or the porosity or saturated conductivity, are available in the Natural Resource

Conservation Service's SOILS-V database. The ARS has made available a software tool, MUUF, (Mapping Unit Use File), which not only provides soil properties from the SOILS-V database, but puts them in a form that can be directly loaded into EPIC input files.

In the northern Virginia scenarios, three soils were used: Glenelg silt loam, hydrologic group B; Galestown sand, hydrologic group A; and Elioak loam, hydrologic group C. In the southern Virginia scenarios the soils used were Pamunkey fine sand loam, hydrologic group B; Buncombe loamy sand, hydrologic group A; and Caroline fine sandy loam, hydrologic group C.

Grass Type

Both cool-season grasses and warm-season grasses are represented in these scenarios. The EPIC model supplies the parameters that determine the growth of each type of crop or plant represented in the simulations. In these simulations, the parameters for a generic cool-season grass was used to represent the behavior of cool-season grasses, and the parameters for Bermuda grass were used to represent warm-season grasses.

As will be shown below, the most important factor in determining nutrient losses from turf grass is the timing of plant uptake. After consultation with the Virginia Department of Conservation and Recreation, it was decided that the nitrogen uptake for cool-season grass should have the following characteristics:

1. Nitrogen uptake begins in March.
2. Peak nitrogen uptake occurs in May.
3. Nitrogen uptake declines in summer months.
4. A second growth peak occurs in the fall, and nitrogen uptake continues into November.

To obtain these characteristics, the growth of the grass was turned off when day length was within 0.75 hours of minimum day length for that latitude, spring growth was delayed until 30% of the potential heat units available for growth had been achieved, and the total potential heat units in the growing season was set at the value for fescue. These measures both shorten the growing season and accelerates growth during the time growth is permitted.

The growth pattern for Bermuda grass is much simpler. Nitrogen uptake begins in April and ends in October. No adjustments were made to the Bermuda grass parameters to change the growing season.

Fertilizer Schedules

The Virginia Department of Conservation and Recreation supplied the fertilizer schedules for these simulations. Eight different fertilizer schedules were represented in these scenarios. The rate and timing of nitrogen and phosphorus applications in the fertilizer schedules are shown in Table 1. Six schedules were used on cool-season grass and five were used on warm-season grass. Two of the schedules represent the practices typical of lawn care companies. Four-Step represents a lawn care program derived from recommendations of lawn care product manufacturers. These three schedules are used on both warm-season grass and cool-season grass.

There are five schedules that represent the recommendations of the Virginia Cooperative Extension Service. The first three are used on cool-season grass, and the last two are used on warm-season grass.

In the simulations with cool-season grass, the grass is cut weekly from May 1 till the first week in September, and then cut every other week until October 15. The reduction in mowing is necessary to allow the grass to grow back in the fall. In the simulations with warm-season grass, mowing was delayed until the last week in May to give the grass time to establish itself. The mowing schedule is otherwise the same as the schedule for cool-season grass.

Denitrification Parameters and Other Adjustments to EPIC

Although EPIC does not need to be calibrated, several model parameters can be adjusted. The adjustment of the coefficient that partitions nitrogen from decaying plant residue will be discussed

Table 1

Fertilization Schedules

Date	lbs N/1000 ft^2	lbs P_2O_5/1000 ft^2	lbs N/ac	lbs P/ac
		Lawn Service I		
Feb 20	0.75	0.11	32.67	2.09
Apr 18	0.75	0.11	32.67	2.09
Jun 10	0.75	0.11	32.67	2.09
Aug 15	0.75	0.11	32.67	2.09
Oct 15	1.0	0.15	43.56	2.85
Dec 10	1.0	0.15	43.56	2.85
Total	5.0	0.74	217.80	14.05
		Lawn Service II		
Feb 20	0.7	0.1	30.49	1.90
Apr 18	0.75	0	32.67	0
Jun 10	0.3	0	13.07	0
Aug 15	0.3	0	13.07	0
Sep 30	1.1	0	47.92	0
Nov 30	1.4	0	60.98	0
Total	4.55	0.1	198.20	1.90
		Four-Step		
Mar 10	1.0	0.2	43.56	3.80
May 10	0.8	0	34.85	0
Jul 10	0.9	0.3	39.20	5.70
Nov 10	0.9	0.1	39.20	1.90
Total	3.6	0.6	156.82	11.40
		Extension Service I		
Sep 10	1.0	0.5	43.56	9.50

Date	lbs N/1000 ft^2	lbs P_2O_5/1000 ft^2	lbs N/ac	lbs P/ac
Oct 10	1.0	0	43.56	0
Dec 10	1.0	0.3	43.56	5.70
Total	3.0	0.8	130.68	15.19
		Extension Service II		
Sep 10	1.0	0.5	43.56	9.50
Oct 10	1.0	0	43.56	0
Nov 10	1.0	0.3	43.56	5.70
Total	3.0	0.8	130.68	15.19
		Extension Service III		
Sep 10	1.5	0.5	65.34	9.50
Oct 10	1.5	0	65.34	0
Dec 10	1.5	0.3	65.34	5.70
Total	4.5	0.8	196.02	15.19
		Extension Service IV		
Apr 15	1.0	0.5	43.56	9.50
May 15	1.0	0	43.56	0
Jun 15	1.0	0.3	43.56	5.70
Total	3.0	0.8	130.68	15.19
		Extension Service V		
Apr 15	1.0	0.5	43.56	9.50
May 15	1.0	0	43.56	0
Jun 15	1.0	0.3	43.56	5.70
Aug 1	1.0	0	43.56	0
Total	4.0	0.8	174.24	15.19

in the section describing the simulations where clippings are returned to the lawn. The most important parameters which can be adjusted are the parameters which control denitrification. It is possible to adjust two denitrification parameters: the rate of denitrification and the level of soil moisture which triggers denitrification. Both of these parameters were left at their default values, given in Williams (1994). Field capacity is the default soil moisture threshold for denitrification. Since any water above field capacity in EPIC will tend to drain to the next soil layer, it is not common for soil moisture to be above field capacity for very long. When the default rate parameter is used, at field capacity or above, approximately 25% of the nitrate in a soil layer will denitrify per day.

The extent of denitrification is perhaps the most controversial issue in determining the nitrogen balance in a crop-soil system. Some believe denitrification losses from well-drained soils are low. They may find the denitrification losses in these simulations too high. Others believe that substantial denitrification can take place even on well-drained soils. For them, the denitrification losses reported here will be too low. Needless to say, until there is general agreement on the level of denitrification under different soil-crop systems, it will be impossible to determine whether the simulated denitrification losses are too high or too low.

Output and Analysis

As explained above, a simulation scenario is defined by its fertilizer schedule, grass, type, soil type, irrigation, and clippings management. Since each soil type is used primarily for one type of grass, soil types can serve as a broader classification scheme for scenarios. Table 2 shows the hydrologic group, grass, type, and weather for each soil type.

For the purposes of this project, the "base case" turf grass management scenario is removing the clippings without irrigation. The impact of the other two management scenarios, removing clippings with irrigation and returning clipping with irrigation, will be compared to the base case. Each of the management scenarios will be run on the complete suite of soil types and fertilizer schedules and discussed in its own section of this report.

Table 2

Turf Grass Simulation Scenarios Characterized By Soil Type

Soil	Hydrologic Group	Grass Type	Weather
Glenelg silt loam	B	Cool-season	National Airport
Galestown sand	A	Cool-season	National Airport
Elioak loam	C	Cool-season	National Airport
Pamunkey fine sandy loam	B	Warm-season	Byrd Field
Buncombe loamy sand	A	Warm-season	Byrd Field
Caroline fine sandy loam	C	Warm-season	Byrd Field

Several different types of model results are supplied in the appendices. The following is a description of the information that is found in each appendix:

Appendix A contains average annual values and other summary statistics, such as the standard deviation, annual maximum, and annual minimum values, for key components of the hydrologic and nitrogen cycles for each scenario. Hydrologic values include the annual precipitation, evapotranspiration, runoff, and percolation. The components of the nitrogen cycle include, annual nitrogen uptake, denitrification, nitrogen content in the removed clippings, and nitrogen losses in runoff and percolation.

In EPIC there are two types of subsurface flow: percolation and lateral flow. Lateral flow occurs when water moves laterally through a soil layer instead of percolating from one soil layer to another. Lateral flow increases as slope increases. In these simulations it was not very significant: lateral flow accounts for about one-half inch of the annual water budget. EPIC also calculates the nitrogen lost in lateral flow. It was generally about 1 lb/ac on an average annual basis. Lateral flow and nitrogen losses in lateral flow are reported in the tables in Appendix A, but will not be discussed.

Appendix B contains monthly averages for precipitation, runoff, evapotranspiration, subsurface flow, and percolation for each combination of soil type, grass type, and turf grass management scenario. The results in these tables come from simulations that use the Lawn Service I fertilizer schedule. For the most part, the simulated hydrologic cycle is not affected by the choice of fertilizer schedule, and these results are typical of the simulations using other fertilizer schedules.

Appendix C contains tables showing the average monthly nitrogen loss in percolation for each soil and fertilizer schedule, grouped by turfgrass management scenario.

Appendix D contains figures showing the average monthly precipitation, evapotranspiration, and percolation corresponding to the tables in Appendix B.

Appendix E contains figures for the first and third management scenarios, showing the average monthly uptake of nitrogen by the turf grass, the average monthly nitrogen loss in percolation, and the average nitrate level in the soil at the end of each month.

Appendix F contains figures showing the average monthly nitrogen losses in percolation and runoff for the first management scenario.

Appendix G contains figures for each soil and fertilization schedule, comparing average monthly percolation losses for each management scenario.

Phosphorus losses are expected to be low and to occur primarily in runoff. Phosphorus losses in general are not discussed, but will be treated in the section which more closely examines nutrient losses in runoff.

First Management Scenario: No Irrigation--Clippings Removed

In the first management scenario there is no irrigation and lawn clippings are removed from the turf. The simulations with cool-season grass will be discussed first, then the simulations with warm-season grass.

Glenelg Silt Loam

Hydrology. Simulations on the Glenelg silt loam used weather data from National Airport in Arlington, VA. The average annual rainfall in the simulation period, 1970-1994, was 39.1 inches. Annual rainfall ranged from 29.3 in to 52.0 inches. Rainfall was distributed fairly evenly over the year. Table B.1 shows the average monthly rainfall. May and July have slightly higher monthly averages, 3.9 inches, than the mean monthly average of 3.3 inches, while January, February, and April have lower monthly averages than the monthly mean, 2.9, 2.6, and 2.8 inches, respectively.

Of the average annual precipitation, 21.5 inches, or 55%, is accounted for by evapotranspiration, and 41% is accounted for by percolation. Simulated annual runoff accounts for less than 5% of the annual water budget on the Glenelg soil. Table B.1 shows the simulated average monthly evapotranspiration, percolation, and runoff. Figure E.1 shows the average monthly precipitation, evapotranspiration, and percolation. Evapotranspiration is highest in the spring, when turfgrass growth is greatest. Evapotranspiration peaks in April, averaging 3.2 inches. Only in April does evapotranspiration exceed precipitation. Evapotranspiration is higher in the summer months, average above 2 inches through August. Percolation, on the other hand, is highest in the winter and early spring. Average percolation is above 1.5 in/mo from November through March, reaching a peak of 2.1 in/mo in December.

Nitrogen Losses. Tables A.1 through A.6 give the simulated average annual nitrogen losses from the Glenelg soil for each of the six fertilizer schedules simulated. In each case, more than three-quarters of the nitrogen is lost in percolation. Table C.1 shows the simulated average monthly nitrogen losses in percolation. Figures F.1 through F.6 show the total average monthly nitrogen losses. The highest monthly nitrogen losses in percolation occur primarily in January, February, and March, and secondarily in December and April. These are the months when the nitrogen uptake by the grass is the lowest.

Figures E.1 through E.6 explain the simulation results. They show the average monthly grass nitrogen uptake, average monthly percolation losses, and the average quantity of soil nitrate at the end of the month. In general, the growing season for cool-season grasses begins in March, reaches its peak in May, declines over the summer, increases again in the fall, and ends in December. Nitrogen uptake from April through November is determined primarily by the availability of soil nitrate. By the end of May nitrogen uptake is in equilibrium with available soil nitrogen from mineralization and fertilization. The grass will use all available soil nitrogen, except when growth is limited in July and August by temperature. During this period, nitrogen losses in percolation are small, since most of the available nitrogen is used by the grass. From December through March and into April, however, the turfgrass nitrogen uptake is minimal, while percolation is at its peak. It is during this period that the nitrogen losses in percolation are highest. Thus, through transpiration demand and nitrogen uptake, the turfgrass growing season determines the timing of both percolation and nitrogen leaching.

The fertilizer schedules determine both turfgrass nitrogen uptake and nitrogen losses in percolation. For the most part, both uptake and percolation losses increase as more nitrogen is applied in fertilizer. Nitrogen losses account for only a small fraction of the nitrogen applied in fertilizer. As tables A.1 through A.6 show, Lawn Service I and II, and Extension Service III have the highest fertilization rates, at 217.8, 198.2, and 196.0 lb/ac/yr, respectively. These three schedules also have the highest losses, at 12.3, 14.7, and 14.1 lb/ac/yr, respectively, and the highest rates of nitrogen uptake, 259.4, 234.2, and 239.4 lb/ac/yr. Extension Service I and II have the lowest rates of fertilization, uptake, and nitrogen losses, while the rates of fertilization, uptake and nitrogen losses for the Four-Step schedule falls somewhere in between the two groups. The nitrogen fertilization rate for the Four-Step, Extension I, and Extension II schedules was 156.8, 130.7, and 130.7 lb/ac/yr, respectively. Nitrogen uptake was 188.4, 171.5, and 179.4 lb/ac/yr, respectively, and average total nitrogen losses were 9.6, 7.4, and 5.4 lb/ac/yr, respectively.

The timing of fertilization is also important. Extension Service I and II differ only in the timing of their last fertilizer application. Extension Service II, which applies the last fertilization on November 10, while the grass is still growing, had less losses than Extension Service I, which applied the last fertilization on December 10, after the grass has stopped growing. Lawn Service I applies more fertilizer than Lawn Service II, but the losses from Lawn Service II are higher because more fertilizer is applied at the end of the growing season.

Nitrogen losses are small, overall, compared with the amount of nitrogen applied in fertilizer and the amount of nitrogen taken up by the turfgrass. Nitrogen losses are about 5% of the applied fertilizer in each schedule. Lawn Service II and Extension Service III have slightly higher loss rates, about 7%, while Extension Service II losses only about 4% of the nitrogen applied in fertilizer. Nitrogen losses generally depend on the average level of soil nitrate in the winter months. The higher the average level of soil nitrate in the winter, the more nitrogen is available to be leached from the soil. Late-season and winter fertilization, such as occurs in the lawn service schedules, thus lead to greater losses. On the other hand, higher levels of soil nitrate in early spring leads to greater nitrogen uptake by the turfgrass and greater spring growth. Both nitrogen uptake and nitrogen yield in the clippings are higher for those schedules which fertilize in February or March. The Extension Service schedules, where fertilization only occurs in the fall, have about half the spring nitrogen uptake as the other schedules, all of which include at least one February or March fertilizer application.

Other components of the nitrogen cycle are less important than fertilization rate, uptake, and leaching losses. About 1 lb/ac/yr of nitrogen is lost in runoff. On average, denitrification accounts for no more than 5.4 lb/ac/yr. 60-75% of the nitrogen taken up by the turfgrass is removed in the clippings.

Galestown Sand

Hydrology. In the simulations on the Galestown sand, a higher proportion of the water budget is accounted for by percolation. Percolation averages about 21.5 in/yr, or about 55% of annual precipitation. Annual percolation is 34% higher than in the simulations on the Glenelg soil. Consequently, evapotranspiration decreases. Simulated evapotranspiration averages 16.7 in/yr, or just over 40% of annual precipitation. Simulated evapotranspiration is 22% less than that simulated on Glenelg soil.

The seasonal pattern of percolation is more evenly distributed in simulations on the Galestown sand. Table B.2 shows the simulated average monthly precipitation, evapotranspiration, runoff, and percolation. Figure D.2 shows the average monthly precipitation, evapotranspiration, and percolation. Percolation averages about 2 in/mo from July through March. It is lower than that level only in April, May, and June. Evapotranspiration generally follows the same pattern it did on the Glenelg soil, but at lower level. As might be expected on a sandy soil, there is practically no runoff.

Nitrogen losses. Given the fact that there is almost no runoff from the Galestown sand, it is not surprising that percolation is the main avenue for nitrogen losses. Tables A.7 through A.12 give the simulated average annual nitrogen losses and summary statistics for the major components of the nitrogen cycle. The relationship between nitrogen losses and fertilization schedules follows the same pattern as found in the simulations on the Glenelg soil. The highest average losses occurred with Lawn Service I, Lawn Service II, and Extension III-- 14.1, 16.5, and 16.1 lb/ac/yr, respectively. The Four-Step program lost 11.1 lb/ac of nitrogen per year. Extension Service I and II once again had the lowest losses, 8.2 and 5.7 lb/ac/yr, respectively. Once again, Extension Service II had the lowest losses overall. Nitrogen losses are 5-15% higher than the losses in the simulations on Glenelg silt loam. This is an increase of anywhere from 0.3 lb to 2.0 lb/yr.

Table C.1 gives the simulated average monthly nitrogen losses in percolation. Figures F.7 through F.12 give the simulated average monthly nitrogen losses. The overall seasonal pattern is the same as that for the simulations on the Glenelg soil. Nitrogen losses in percolation occur primarily in the winter and early spring, before the nitrogen uptake by turfgrass peaks. Figures E.7 through E.12 show the average monthly nitrogen uptake by turfgrass, average monthly percolation losses, and the average end-of-the-month soil nitrate level. The overall pattern is almost identical to that found in the simulations on the Glenelg soil. Greater percolation in the Galestown simulations does not lead to a proportional increase in nitrogen losses in percolation, because nitrogen losses remain low during the growing season. The average annual nitrogen uptake by turfgrass and the average annual nitrogen content removed in the clippings show little difference from the Glenelg simulations. Slightly higher values of uptake in most Galestown simulations, no more than 1-2 lb/ac/yr, probably reflect lower nitrogen losses in denitrification. Denitrification losses ranged from 1.3 lb/ac/yr using the Extension II schedule to 3.3 lb/ac/yr using Lawn Service II. These losses are approximately 40% less than the corresponding denitrification losses in the Glenelg simulations. Denitrification losses are lower because the Galestown sand drains more quickly than the Glenelg silt loam.

Elioak Loam

Hydrology. The Elioak loam belongs to hydrologic group C. It produces more runoff and drains more slowly than the Glenelg silt loam. More than 10% of annual average annual precipitation of 39.1 in/yr, 4.3 inches, is lost in runoff. This is three times the runoff in the simulations on the Glenelg soil. As might also be expected, percolation is less on the Elioak soil. Percolation accounts for only a little more than one-quarter of average annual precipitation, about 30% less than in the simulations on Glenelg soil. 60% of average annual precipitation, or 23.6 inches, is accounted for by evapotranspiration. This is 10% more than on the Glenelg soil.

Table B.3 shows the simulated average monthly precipitation, evapotranspiration, runoff, lateral flow, and percolation. Figure E.3 shows the average monthly precipitation, evapotranspiration, and percolation. Monthly evapotranspiration follows the same pattern as in the Glenelg simulations. Simulated average monthly percolation is never more than 2 in/mo. From April through August, it is less than 0.5 in/mo. On average, runoff is slightly lower in the first half of the year, from January through May, than in the rest of the year. September, on average, has noticeably more runoff, 0.7 in/mo.

Nitrogen losses. Nitrogen losses follow a different pattern in the Elioak simulations than in the simulations for the Glenelg and Galestown soils. Because the Elioak simulations have more runoff and less percolation, more nitrogen is lost in runoff and less in percolation than on the other two soils. Tables A.13 through A.18 show the simulated average annual nitrogen losses, nitrogen uptake, and nitrogen removed in the clippings for the Elioak simulations. The bulk of the nitrogen losses occur in runoff. Total average annual nitrogen losses are less for each fertilizer schedule than on the other two soils, except for Extension Service II, where losses are slightly higher than on the Glenelg soil. The Extension II schedule still produces the lowest nitrogen losses of any schedule. In fact, for all three soils, the relative ranking of the fertilizer schedules, when ordered from the lowest losses to the highest, is the same: Extension Service II, Extension Service I, Four-Step, Lawn Service I, Extension Service III, Lawn Service II. On the Elioak soil, however, the fertilizer schedules with higher losses have considerable less losses than on the other two soils. Total average annual losses on the Elioak soil range from 6.2 lb/ac/yr to 11.1 lb/ac/yr, so the range of losses is not as great as for the other two soils.

Figures F.13 through F.18 show the average monthly nitrogen losses. Figures E.13 through E.18 show the average monthly nitrogen uptake by turfgrass, average monthly percolation losses, and the average end-of-the-month soil nitrate level. In general, the pattern of nitrogen uptake is the same as in the previous scenarios. Simulated average annual nitrogen uptake is somewhat higher on the Eliaok soil, because nitrate leaching occurs at a slower rate. Nitrogen losses in denitrification are higher than on the Galestown soil and comparable to the losses on the Glenelg soil.

Percolation losses remain higher in the winter, but since they do not dominate total nitrogen losses, there is no general seasonal pattern to nitrogen losses. Runoff losses tend to occur in those months where fertilization occurs, since more nitrogen is in the surface layer after fertilization. As a result, nitrogen losses are no longer driven by hydrology, but by the fertilization schedules, so the seasonal pattern of nitrogen losses differs according to the fertilization schedule used. The lowest average annual nitrogen losses in runoff occurred when the Extension Service I schedule was used. Lawn Service II had the highest average annual losses, 6.1 lb/ac.

Warm-Season Grass

All of the simulations representing warm-season grasses use weather data from Byrd Field (Richmond International Airport). Average annual precipitation for the simulation period, 1970-1994, was 43.4 in/yr. Annual precipitation ranged from 28.3 to 61.3 in/yr. Average monthly precipitation is shown in Tables B.4 through B.9, or in Figures D.4 through D.9. Average monthly precipitation is above 4 in/mo in March, May, July, and August. It is below average, but still above 3 in/mo, from November through February.

The growing season for warm-season grass is shorter than that for cool-season grass. As shown in Figures E.19 through E.33, nitrogen uptake begins in April, peaks in May, and tails off October and November. Annual nitrogen uptake and the nitrogen content removed in clippings are generally less than that for cool-season grass when comparable fertilization schedules are used.

Pamunkey Fine Sandy Loam

Hydrology. Table A.19 shows the summary statistics for annual evapotranspiration, runoff, and percolation using the Lawn Service I schedule on the Pamunkey soil. Summary statistics for these simulations are given in Tables A.20 through A.23. Average annual percolation is greater than average annual evapotranspiration. Simulated percolation averages 21.3 in/yr, half of annual precipitation. Evapotranspiration averages 20.0 in/yr. Runoff accounts for 1.7 in/yr on average, or less than 5% of annual precipitation.

Table B.4 shows the average monthly evapotranspiration, percolation, and runoff. Figure D.4 shows average monthly precipitation, evapotranspiration, and percolation. Simulated evapotranspiration is at a minimum in December and January, when it is less than 1 in/mo.

Average monthly evapotranspiration peaks in May at 3.0 in/mo, and declines thereafter. The pattern of simulated percolation is less smooth. Average monthly percolation is less than 1.5 inches in April, May, and June, and greater than 2.0 inches in January and March, and fluctuates between 1.5 and 2.0 inches in the other months.

Nitrogen losses. Nitrogen losses vary widely with fertilizer schedule. Tables A.19 through A.23 show summary statistics for simulated annual nitrogen losses, nitrogen uptake, and the nitrogen content removed in the clippings. Table C.1 shows average monthly nitrogen losses in percolation. Figures E.19 through E.23 show average monthly nitrogen uptake, average monthly nitrogen losses, and average end-of-the-month nitrate levels in the soil. Figures F.19 through F.23 show average monthly nitrogen losses.

Nitrogen losses in the simulations using the Lawn Service I, Lawn Service II, and Four-Step fertilizer schedules occur by the same mechanisms as in the simulations using cool-season grass on the Glenelg soil. Total losses for the Lawn Service I, Lawn Service II, and Four-Step simulations are 27.5, 28.4, and 13.9 lb/ac/yr, respectively, of which the bulk is lost in percolation--24.1, 28.4, and 11.7 lb/ac/yr, respectively. Percolation losses occur primarily from January through May, and peak in March. The level of losses depends on the level of soil nitrate in the winter and early spring. The lawn service schedules produce substantially more losses with warm-season grass than cool-season grass for two reasons. First, the growing season for warm-season grass starts later, and thus leaves the soil nitrate more vulnerable to leaching in the early spring. An additional consequence of the later start to the growing season is that denitrification losses substantially increase, and are comparable to nitrogen losses in percolation.

The lawn service schedules also produce greater nitrogen losses for a second reason: the late summer and fall fertilizations are not taken up by the turfgrass, but are added to the pool of soil nitrogen that is carried over into the next growing season. This again leads to greater nitrogen leaching losses in the winter and early spring. These factors are also at work when the Four-Step schedule is simulated, but since the nitrogen fertilization rate is lower than the rates for the lawn service schedules, the losses are also lower.

Extension Service IV has very low nitrogen losses, because the nitrogen is applied just before there is a demand for it by the turfgrass. Average annual losses are only 4.1 lb/ac, of which 2.7 lb/ac are in percolation. As Figure E.22 shows, there is little carry-over of nitrate between one growing season and the next. Soil nitrate levels are low in the winter and early spring when the soil nitrate is most vulnerable to leaching. As Figure F.22 shows, although nitrogen losses occur in March, most of the losses do not occur until after fertilizer is applied in April. Extension Service V differs from Extension Service IV by having an additional nitrogen application August 1. This leads to some increase in losses, although over 90% of the additional nitrogen is taken up by the turf. When the Extension V schedule is simulated, an average 10.4 lb/ac/yr of nitrogen is lost, 8.1 lb/ac/yr in percolation. There is a slight increase in the amount of soil nitrate in the winter months. This leads to greater losses in the winter and early spring. As a result, nitrogen losses for the Extension V simulation are distributed fairly evenly throughout the year.

Buncombe Loamy Sand

Hydrology. The Buncombe loamy sand belongs to hydrologic group A--excessively drained soils. As can be expected, very little runoff occurs from this soil. Table A.24 gives annual summary statistics for Lawn Service I simulation. Simulated average annual evapotranspiration was 19.0 in/yr. Simulated average annual percolation was 23.8 in/yr. Annual percolation averaged 2.5 inches more, and annual evapotranspiration averaged 1.0 inches less, than the simulations on the Pamunkey soil.

Table B.5 gives the average monthly evapotranspiration and percolation typical of simulations on the Buncombe soil. Figure D.5 shows average monthly precipitation, evapotranspiration, and percolation. The overall pattern is similar to that on the Pamunkey soil, except that percolation is proportionately greater and evapotranspiration proportionately less on the Buncombe soil.

Nitrogen losses. The effect of the fertilizer schedules on nitrogen losses is even more pronounced on the Buncombe soil than on the Pamunkey soil. Although percolation increases by only 12%, nitrogen losses in percolation increased by as much as 70% in the simulations using the lawn service schedules and the four-step program. Total average annual nitrogen losses for Lawn Service I, Lawn Service II, and the Four-Step schedules on Buncombe soil are 42.9, 46.8, and 23.7 lb/ac, respectively. All but about one pound of these losses are in percolation. Percolation losses increased by 70%, 78%, and 93%, respectively, compared to the corresponding Pamunkey simulations. Simulated nitrogen losses also larger when the extension service schedules are used, but not as dramatically larger. Losses from the simulation using Extension Service IV remain low. Total average annual nitrogen losses are only 5.3 lb/ac. Total average annual nitrogen losses from Extension V are 12.4 lb/ac, an increase over the corresponding Pamunkey scenario of 19%.

Figures E.24 through E.28 show average monthly nitrogen uptake, average monthly nitrogen losses, and average end-of-the-month nitrate levels in the soil. Figures F.24 through F.28 show average monthly nitrogen losses. Both the pattern of nitrogen losses and the general pattern of nitrogen uptake and soil nitrate levels are the same for both the Pamunkey simulations and the Buncombe simulations. The large increase in nitrogen losses on the Buncombe soil comes not only from the increase in percolation, but also from the decrease in denitrification. Because the Buncombe soil drains faster than the Pamunkey soil, it is less frequently above field capacity and thus less susceptible to denitrification. Average annual denitrification decreases from 42% to 50% in the Buncombe scenarios. The decrease in nitrogen uptake and in the nitrogen content removed in the clippings is due to the increase in nitrogen losses prior to the growing season.

Caroline Fine Sandy Loam

Hydrology. Table A.29 shows summary statistics for annual hydrology for the simulation using Lawn Service I on Caroline fine sandy loam, a moderately well-drained C soil. Simulated evapotranspiration accounts for 22.0 in/yr, or more than half of average annual precipitation. Simulated average annual runoff is 6.8 in/yr and average annual percolation is 14.3 in/yr, or about 16% and 33% of the annual precipitation. There is four times as much runoff from the Caroline soil as from the Pamunkey soil. Evapotranspiration is also larger by 10%, while percolation is

40% less than the simulations on Pamunkey soil.

Table B.6 shows the average monthly evapotranspiration, percolation, and runoff from the Lawn Service I schedule on the Caroline soil. Figure D.6 shows average monthly precipitation, evapotranspiration, and percolation. Average monthly percolation is 1 in/mo or less from May through September. Otherwise, the overall seasonal pattern of percolation is similar to that in the simulations on the Pamunkey soil, although average monthly percolation is at least 0.3 in/mo less between October and May. Evapotranspiration follows the pattern found on the Pamunkey soil, with slightly larger values.

Nitrogen losses. The simulations on the Caroline soil have lower nitrogen losses in percolation and higher nitrogen losses in runoff than the other warm-season grass scenarios. Tables A.29 through A.33 show the annual summary statistics for the simulations on the Caroline soil. Simulated total average annual nitrogen losses were 26.1, 26.4, 16.3, 7.9, and 13.7 lb/ac, for the simulations using the Lawn Service I, Lawn Service II, Four-Step, Extension IV, and Extension V schedules, respectively. Average annual nitrogen losses in runoff were 12.2, 11.2, 8.3, 5.7, 9.8 lb/ac, respectively, and average annual percolation losses were 12.6, 14.0, 7.1, 1.8, and 3.4 lb/ac, respectively. Thus, in the simulations using the lawn service schedules, nitrogen losses in percolation accounted for a little more than half of total nitrogen losses, in the simulation using the Four-Step schedule, nitrogen losses in percolation accounted for little less than half of total nitrogen losses, while in the simulations using the extension service schedules, nitrogen losses in runoff accounted for the bulk of total nitrogen losses. Figures F.29 through F.33 show average monthly nitrogen losses. Runoff losses tend to occur in the period after fertilization occurs, but, when the lawn service schedules are used, there are also significant nitrogen losses in runoff throughout the winter and early spring.

Figure E.29 through E.33 show the average monthly nitrogen uptake, average monthly nitrogen losses in percolation, and average end-of-the-month nitrate levels in the soil. The patterns of nitrogen uptake on the Caroline soil do not differ significantly from the patterns seen on the

Pamunkey soil, although the amount of nitrogen uptake and the nitrogen content removed in the clippings are both smaller in the Caroline scenarios. Denitrification losses are much larger in the simulations on the Caroline soil, because the slower-draining soil is closer to field capacity for longer periods of time. Simulated average annual nitrogen losses in denitrification were 40.2, 43.6, 22.7, 5.7, and 11.7 lb/ac, for the simulations using Lawn Service I, Lawn Service II, Four-Step, Extension IV, and Extension V schedules, respectively. These losses are twice as high as the denitrification losses in the corresponding simulation on Pamunkey soil, and explain the lower level of nitrogen uptake found in the Caroline simulations. On the Caroline soil, more nitrogen is lost in the early spring through denitrification before it can be taken up by the turfgrass.

Cool-Season Grass on Southern Virginia Soils

The growth of cool-season grass was simulated on three soils used for growing warm-season grasses. Weather data from Byrd Field was also used. The results were compared not only to the simulations using warm-season grass, but to the simulations growing cool-season grass in northern Virginia.

Pamunkey fine sand loam. Tables A.34 through A.39 show the summary statistics for simulations representing cool-season grass on the Pamunkey soil. There was more evapotranspiration and less percolation when cool-season grass was grown than when warm-season grass was grown. Simulated average annual evapotranspiration was 22.3 in/yr and average percolation was 19.0 in/yr with cool-season grass, compared to 20.0 in/yr and 21.3 in/yr, respectively, with warm-season grass. Simulated total nitrogen losses were lower when cool-season grass was grown. Total average annual nitrogen losses ranged from 3.6 to 9.9 lb/ac/yr with cool-season grass, compared to 4.1 to 28.4 lb/ac/yr with warm-season grass. Total nitrogen losses using the Extension Service II schedule with a cool-season grass were lower than any schedule with either grass type.

Despite the fact that the Richmond climate is wetter than metropolitan Washington, leading to greater percolation, nitrogen losses from Pamunkey soil when a cool-season grass was grown were less than losses from the Glenelg soil under the same fertilization schedule. Nitrogen uptake is greater on the Pamunkey soil because of the warmer weather in the metropolitan Richmond area. Ranking the fertilizer schedules by losses produces the same results on the Pamunkey soil and the Glenelg soil. Extension Service II yields the lowest losses, and Lawn Service II yields the highest losses.

Buncombe loamy sand. Tables A.40 through A.45 show the summary statistics for simulations representing cool-season grass on the Buncombe soil. Just as was the case on the Pamunkey very sandy loam, there was more evapotranspiration and less percolation when cool-season grass was grown than when warm-season grass was grown. Simulated average annual evapotranspiration was 21.2 in/yr and average percolation was 21.6 in/yr with the cool-season grass, compared to 19.0 in/yr and 23.8 in/yr, respectively, with the warm-season grass. Simulated total nitrogen losses generally were lower when the cool-season grass was grown. Total average annual nitrogen losses ranged from 5.4 to 16.3 lb/ac/yr with cool-season grass, compared 5.3 to 46.8 lb/ac/yr with a warm-season grass. The simulation which used the Extension Service IV schedule on a warm-season grass, however, had the lowest losses overall, 5.3 lb/ac/yr. The simulation representing the use of Extension II on cool-season grass was comparable, with total average annual nitrogen losses of 5.4 lb/ac.

The results from the simulations with a cool-season grass on the Buncombe soil are very similar to the results from the corresponding simulations using the Galestown sand. Despite the higher rainfall, the Buncombe simulations produce slightly less percolation. Total nitrogen losses are almost identical for the two soils under the same fertilizer schedules, differing by no more than 0.7 lb/ac/yr.

Caroline fine sandy loam. Tables A.46 through A.51 show the summary statistics for simulations representing cool-season grass on the Caroline soil. Just as was the case for the other two soils, there was more evapotranspiration and less percolation when cool-season grass was grown than when warm-season grass was grown. Simulated average annual evapotranspiration was 23.9 in/yr and average percolation was 12.6 in/yr with cool-season grass, compared to 22.0 in/yr and 14.3 in/yr, respectively, with warm-season grass. Simulated average annual runoff was a 6.7 in/yr with a cool-season grass and 6.8 in/yr with the warm-season grass, an insignificant difference. Simulated total nitrogen losses generally were lower when the cool-season grass was grown. Total average annual nitrogen losses ranged from 6.3 to 14.6 lb/ac/yr with cool-season grass, compared with 7.9 to 26.4 lb/ac/yr with a warm-season grass. Once again, simulation using the Extension Service II schedule on a cool-season grass had the lowest losses overall.

When compared to the corresponding simulations on the Elioak soil, the simulations with cool-season grass on the Caroline soil generally have higher losses. These higher losses are due to the higher runoff from the Caroline soil. Average annual runoff from the Caroline soil is 6.7 in/yr, compared to 4.3 in/yr from the Elioak soil.

The Second Management Scenario: Irrigation--Clippings Removed

In these simulations the turfgrass was irrigated so that soil water in the root zone was kept at field capacity. For cool-season grass, the turf was irrigated from May 1 to September 30, and for warm-season grass, the turf was irrigated from the last week in May till September 30, so that the period in which irrigation takes place roughly corresponds to the period in which the lawn is mowed.

Effects of Irrigation on Hydrology

Table 3 shows the average monthly and average annual simulated irrigation for each soil. The results are from the simulations using the Lawn Service I fertilizer schedule. These results are typical of the simulations for other fertilizer schedules.

Simulated average annual irrigation ranges from 11.2 in/yr on the Caroline fine sandy loam to 19.9 in/yr on the Elioak loam. Monthly irrigation tends to decrease as the growing season progresses. It should be recalled that the average monthly irrigation for May for warm-season grass represents only one week of irrigation. Irrigation rates are comparable with precipitation rates. Monthly irrigation is about three-quarters of monthly precipitation for the cool-season grass and two-thirds of monthly precipitation for the warm-season grass, although, since precipitation in the Richmond area is higher in the summer months than precipitation in the metropolitan Washington region, the Pamunkey and Buncombe soils receive more irrigation than any of the northern Virginia soils except for the Elioak soil.

Table 4 shows the average annual increase in evapotranspiration and percolation for each soil. For most of the soils, about 60% of the irrigation water is accounted for by an increase in evapotranspiration and 40% is lost in additional percolation. On the Caroline soil, which has the lowest average annual irrigation, about 70% of the irrigation water is accounted for by additional evapotranspiration. Simulated average annual percolation increases by about 20% on most soils, though the Glenelg soil has an increase of 35% and the Elioak soil has an increase of 68%.

Table 3

Average Monthly Irrigation (in/ac)

Lawn Service I

Month	Glenelg	Galestown	Elioak	Pamunkey	Buncombe	Caroline
Jan	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.0	0.0
Mar	0.0	0.0	0.0	0.0	0.0	0.0
Apr	0.0	0.0	0.0	0.0	0.0	0.0
May	4.1	3.4	5.1	1.0	1.0	1.0
Jun	3.2	2.2	4.0	3.8	3.6	3.1
Jul	3.1	2.3	4.0	3.3	3.2	2.5
Aug	2.8	2.1	3.7	3.2	3.0	2.3
Sep	2.5	1.6	3.0	2.7	2.5	2.3
Oct	0.0	0.0	0.0	0.0	0.0	0.0
Nov	0.0	0.0	0.0	0.0	0.0	0.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0
Annual	15.7	11.9	19.9	14.0	13.3	11.2

Tables B.10 through B.15 show average monthly hydrology typical for the simulations representing this management scenario. Average monthly precipitation, evapotranspiration, and percolation are shown in Figures D.10 through D.15. One effect of irrigation is to shift the peak of evapotranspiration later into the growing season, so that the highest evapotranspiration tends to occur in June or July.

Effect of Irrigation on Nitrogen Losses

It should be expected that irrigation would increase nitrogen losses by increasing percolation and nitrogen leaching. For the most part, that is the case, though the effect of irrigation on nitrogen

Table 4

Average Annual Irrigation

Increase in Evapotranspiration and Percolation From Irrigation (in/ac)

Lawn Service I

Soil	Irrigation	Additional Evapotranspiration	Additional Percolation
Glenelg silt loam	15.7	9.6	5.7
Galestown sand	11.9	6.8	5.0
Elioak loam	19.9	11.8	7.5
Pamunkey fine sandy loam	14.0	8.6	5.1
Buncombe loamy sand	13.3	8.2	4.9
Caroline fine sandy loam	11.2	7.8	3.1

losses is less pronounced than its effect on percolation, and the increase in nitrogen losses is much smaller than the increase in percolation on all soils. The increase in percolation occurs in the months when the turf is irrigated during the growing season, or in October, just after irrigation has ended. The nitrogen demand from turfgrass is high during this time, and the concentration of nitrogen in the soil is kept low by turfgrass demand. Thus little additional nitrogen is leached from the soil, despite the large increase in percolation during those months.

Tables A.52 through A.83 give summary statistics of average annual nitrogen losses for each simulation using irrigation. Table 5 shows the percent increase in total nitrogen losses for each soil and fertilizer schedule when irrigation is used. Increases in average annual nitrogen losses is 10% or less for all soils and all schedules except for Extension Service schedules on the Pamunkey and Buncombe soils. The percent increase is larger for these schedules because their nitrogen losses without irrigation were small. For the most part, the increase in nitrogen losses is less than 5%, and on the C soils, nitrogen losses even decrease when irrigation is applied.

Table C.2 shows the average monthly nitrogen losses in percolation for simulations modeling

Table 5
Percent Change in Total Nitrogen Losses
With Respect to First Management Scenario
Irrigation--Clippings Removed

Schedule	Glenelg	Galestown	Elioak	Pamunkey	Buncombe	Caroline
Lawn Service I	9%	9%	4%	4%	3%	-0%
Lawn Service II	7%	8%	8%	4%	2%	1%
Four-Step	5%	5%	-5%	10%	8%	2%
Extension I	3%	1%	-3%	----	----	----
Extension II	2%	2%	-3%	----	----	----
Extension III	3%	3%	0%	-----	-----	----
Extension IV	----	----	----	12%	17%	-11%
Extension V	----	----	----	11%	15%	-10%

irrigation. Figures F.1 through F.6 compare average monthly nitrogen losses in percolation from each management scenario on each soil. The losses for simulations representing cool-season grass using extension service schedules are low because most of the fertilizer is applied after irrigation stops. The increase in nitrogen losses in percolation ranges from 0.0 to 0.5 lb/ac, leading to the small percent increases in total losses, ranging from 1 to 3%. The large percent increase in total average annual nitrogen losses on A and B soils with warm-season grass using the extension service schedules is caused by a relatively small increase in average annual nitrogen losses in percolation. The increase in losses ranges from 0.6 to 1.7 lb/ac.

When the lawn service schedules are used on cool-season grass, the increase in annual nitrogen losses in percolation ranges from 0.9 lb/ac to 1.2 lb/ac, with the largest increases in average monthly losses in percolation occurring in May. These increases lead to a percent increase in total nitrogen losses of 7 to 9 %. The simulations using lawn service schedules on warm-season grass have about the same range of increase in average annual nitrogen losses in percolation, 0.8 to 1.2

lb/ac, but because their total nitrogen losses without irrigation are higher, the percent increase in total nitrogen losses caused by irrigation only ranges for 2 to 4%.

The largest increase in average annual nitrogen losses in percolation, 1.8 lb/ac, occurs on the Buncombe soil with the Four-Step schedule. This leads to a 8% increase in total nitrogen losses when compared to the simulation without irrigation. On the Pamunkey soil, the increase in average annual nitrogen losses in percolation when the Four-Step schedule is used, is 1.3 lb/ac, which results in an increase in total nitrogen losses of 10%. On cool-season grass, when the Four-Step schedule is used, the increase in nitrogen losses in percolation ranges from 0.3 to 0.5 lb/ac, and the corresponding percent increase in total nitrogen losses is smaller, about 5%.

Nitrogen losses in runoff decrease when turfgrass is irrigated. The decrease occurs because, for those fertilizer applications that occur during the time the grass is irrigated, irrigation transports nitrogen fertilizer below the surface layer making it less vulnerable to runoff. The impact is not noticeable on A and B soils, where runoff losses are small, but is significant on the C soils, where it leads to a decrease in total nitrogen losses. The decrease in nitrogen losses in runoff ranged from 0.2 to 0.7 lb/ac/yr on the Elioak soil, with a small increase when the Lawn Service II schedule was used. The decrease in losses on the Caroline soil was1.0 lb/ac/yr or greater from all fertilization schedules except the Four-Step. Runoff losses decreased by 2.5 lb/ac/yr when the Extension V schedule was used on the Caroline soil.

In most simulations, denitrification also increased by about one pound per year with irrigation. There was also a small decrease in the nitrogen taken up by the turfgrass and the nitrogen removed in the clippings, probably due to the increases in denitrification and total nitrogen losses.

Third Management Scenario: Irrigation--Clippings Returned

Lawn clippings returned to the turf represent an additional source of nutrients. As they decay, they release nitrate to the soil which is then available to the turfgrass. The main goal of this section is to determine (1) whether additional nitrogen losses occur because of the nitrogen supplied by the clippings, (2) how much additional nitrogen is lost, and (3) what fertilization rate would lead to losses equivalent to those described in the previous sections. Simulations were performed to examine the effect of leaving lawn clippings on the turf. In these simulations, the same fertilizer schedules were used that had been used previously, and the turfgrass was irrigated as described in the last chapter.

The Effect of Returning Clippings on Turfgrass Nitrogen Uptake

As clippings decay, they release readily available forms of nitrogen, and also add more resistant organic nitrogen to the soil. This organic nitrogen may also slowly mineralize and become available to the grass over a longer period of time. EPIC represents the decay of plant residues by partitioning the nitrogen in the residues into two pools. As the residues decay, some of nitrogen enters the nitrate pool; the remainder enters the organic nitrogen pool. There exists an adjustable parameter which sets the fraction which goes to each pool. As described in the model documentation, 80% of the nitrogen from decayed residues should enter the nitrate pool, and 20% should enter the organic nitrogen pool. This partitioning led to unsatisfactorily large annual turfgrass nitrogen uptake rates.

Starr and DeRoo (1981) used radioactively tagged nitrogen to determine the uptake of nitrogen by turfgrass from fertilizer, the soil, and grass clippings. They found that returning the clippings increased nitrogen uptake in turfgrass by 19%, 74%, and 41% per year over a three year study. In the absence of any other information, the partition rate was adjusted so that returning the clippings increased the nitrogen uptake rate by about 50%. The partition coefficient was set so that 30% of the nitrogen from decaying residue is released as nitrate and the rest is added to soil organic nitrogen.

Table 6 shows the percent increase in annual nitrogen uptake rates, relative to the simulations using the second management scenario, when the clippings are returned. The increase in nitrogen uptake by cool-season grass averages about 55% on the three soils. The increase in nitrogen uptake by the warm-season grass is much less, about 30%, because the growth of the warm-season grass is not limited by available nitrogen. Not all of the nitrogen released from the clippings can be used by the warm-season grass. This leads to a substantial increase in nitrogen losses, as will be shown below.

Table 6
Percent Change in Turfgrass Nitrogen Uptake
With Respect to Second Management Scenario
Irrigation--Clippings Returned

Schedule	Glenelg	Galestown	Elioak	Pamunkey	Buncombe	Caroline
Lawn Service I	55%	47%	60%	23%	25%	25%
Lawn Service II	55%	48%	61%	32%	36%	35%
Four-Step	65%	56%	72%	32%	34%	33%
Extension I	56%	48%	63%	----	----	----
Extension II	51%	44%	58%	----	----	----
Extension III	50%	44%	56%	----	----	----
Extension IV	----	----	----	40%	40%	39%
Extension V	----	----	----	21%	19%	20%

The Effect of Returning Clippings on Hydrology

Tables B.16 through B.21 show the simulated average monthly and average annual evapotranspiration, runoff, and percolation when the clippings are returned for both cool-season grass and warm-season grass. The effect of the returned clipping on hydrology is slight. For cool-season grass, the increase in turfgrass growth, as marked by the increase in nitrogen uptake, leads to a slight increase in evapotranspiration of less than 0.5 in/yr and a corresponding decrease in percolation of about 0.2 in/yr, compared to the simulations using irrigation but removing the clippings. Returning lawn clippings has almost no impact on warm-season grass, since there is a much smaller increase in turfgrass growth for warm-season grass when the clippings are returned.

The Effect of Returning the Clippings on Nitrogen Losses

Tables A.85 through A.117 present summary statistics for the major components of the nitrogen cycle for each simulation where clippings are returned. Table C.3 shows the average monthly nitrogen losses in percolation.

The increase in nitrogen losses is substantial, especially when warm-season grass is simulated. Table 7 shows the percent increase in nitrogen losses when clippings are returned relative to the simulations which use irrigation but remove the clippings. The increase ranges from 27% to 80% for simulations with cool-season grass and from 37% to 330% for simulations with warm-season grass, though it should be noted that many, but not all, of the larger increases on warm-season grass occur when the extension service schedules are used. These simulations had very low nitrogen losses initially.

Figures G.1 through G.18 show average monthly losses nitrogen losses in percolation for simulations with cool-season grass under the three management scenarios discussed so far: no irrigation with clippings removed, irrigation with clippings removed, and irrigation with clippings returned. For the most part, when clippings are returned, percolation losses follow the same patterns discussed previously. The highest losses occur in the winter and early spring for all fertilizer schedules. There are some small additional losses in the summer when the grass is irrigated. When clippings are returned, all fertilizer schedules show an disproportionate increase in losses in March. For the Lawn Service I, Lawn Service II, and Extension Service III schedules, which have the highest application rates, there is also a pronounced increase in nitrogen losses in percolation in May. The Four-Step schedule shows small but noticeable increases in percolation losses in the summer months, because the decaying clippings diminish the need for the July fertilizer application.

Table 7

Percent Change in Total Nitrogen Losses

With Respect to Second Management Scenario

Irrigation--Clippings Returned

Schedule	Glenelg	Galestown	Elioak	Pamunkey	Buncombe	Caroline
Lawn Service I	63%	56%	80%	119%	76%	54%
Lawn Service II	46%	38%	48%	81%	44%	37%
Four-Step	28%	27%	30%	131%	82%	59%
Extension I	42%	40%	31%	----	----	----
Extension II	75%	66%	42%	----	----	----
Extension III	54%	43%	63%	----	----	----
Extension IV	----	----	----	330%	268%	124%
Extension V	----	----	----	266%	262%	124%

Figures E.34 through E.51show the average monthly nitrogen uptake, and average end-of-the-month soil nitrate levels for simulations in which the clippings are returned. In general, soil nitrate levels and nitrogen uptake follow the same pattern as found in the simulations without irrigation. Nitrogen uptake occurs at a higher level, and the level of soil nitrate is higher in the winter and early spring, leading to higher losses, but generally the grass is able to take up all the nitrogen available from the fertilizer applications and the mineralization of nitrogen in the clippings.

This is not the case in the simulations with warm-season grass. Figures E.52 through E.66 show the average monthly nitrogen uptake, and average end-of-the-month soil nitrate levels for simulations in which the clippings are returned. Soil nitrate levels remain high during the growing season, demonstrating that the grass cannot use all of the nitrogen that is available. This leads to higher nitrogen losses in percolation, both during the growing season and in the winter and early spring. Figures G.19 through G.33 show the average monthly nitrogen losses in percolation for simulations with warm-season grass under the three management treatments simulated. When clippings are returned, percolation losses are noticeably higher during the growing season, because nitrate unused by the grass can be leached from the soil. This effect is most noticeable in the simulations using the extension service schedules. When clippings are not returned, the level of soil nitrogen drops to zero by August in simulations using the Extension Service IV schedule. The level of soil nitrate is less than 10 lb/ac in the winter and early spring, before the April fertilizer application. Similarly, when clippings are not returned and the Extension V schedule is used, the level of soil nitrate drops to 10 lb/ac or less in the fall and stays at that level till fertilizer is applied in April. When clippings are returned, however, soil nitrogen levels generally remain above 10 lb/ac during the growing season for simulations using Extension Service IV and 20 lb/ac for simulations using Extension Service V. The level of soil nitrate ranges from 20-40 lb/ac during the winter and early spring with Extension Service IV and 40-60 lb/ac with Extension Service V. These levels of soil nitrate cause there to be significant losses of nitrogen in percolation distributed throughout the year. Average annual nitrogen losses in percolation increased from 3.3, 5.7, and 2.1 lb/ac, on the Pamunkey, Buncombe, and Caroline soils, respectively, under the second management scenario, to 17.8, 21.8, 15.7 lb/ac, when clippings were returned, for simulations using the Extension IV schedule. For simulations using the Extension V schedule, average percolation losses increased from 9.5, 13.3, and 4.4 lb/ac/yr to 38.9, 49.8, and 15.8 lb/ac/yr, for the Pamunkey, Buncombe, and Caroline soils, respectively.

With one exception, the relative losses from the fertilizer schedules remained unchanged. That is to say, if the schedules were ranked according to the total nitrogen losses associated with them, the ranking is not affected by irrigation or clippings management. The one exception is that on the Elioak soil, when clippings are returned, the Extension Service I schedule has 0.1 lb/ac less total average annual nitrogen losses than the Extension II schedule. The Extension Service II schedule produces less percolation losses, but is more vulnerable to runoff than the Extension Service I schedule.

Reducing Nitrogen Losses By Reducing Fertilization Rates

Since the mineralization of nitrogen in the clippings supplies some of the nitrogen needed by the turfgrass, less nitrogen fertilizer may be necessary to sustain turfgrass growth. Simulations were performed to determine what level of nitrogen fertilization when clippings are returned would have the same level of total nitrogen losses as when clippings are removed. For each fertilization schedule, the rate of nitrogen application was uniformly reduced until the losses when the clippings were returned were at the same level as when they were removed.

Table 8 shows the percentage of the fertilizer application rate when clippings were returned that yielded the same level of losses as when they were removed. Different rates were determined for warm-season grass and cool-season grass. Cool-season grass could tolerate a higher nitrogen application rate than warm-season grass. When clippings are returned, cool-season grass would yield the same level of nitrogen losses as when clippings are removed if only about 80% of the nitrogen in the fertilization schedules were applied. For cool-season grass, the appropriate percentage of the original application rate varies somewhat with the fertilization schedule, but not

Table 8

Percent of Fertilizer Application With Clippings Returned

With Total Nitrogen Losses Equivalent to When Clippings Are Removed

Irrigation

Schedule	Cool-Season Grass	Warm-Season Grass
Lawn Service I	75-80%	65-70%
Lawn Service II	80%	70-75%
Four-Step	85%	65-70%
Extension Service I	80%	----
Extension Service II	80%	----
Extension Service III	75-80%	----
Extension Service IV	----	45%
Extension Service V	----	55%

as much as it varies for warm-season grass. For warm-season grass, the lawn service schedules and the four-step program need to reduce fertilizer application rates to about 65-75% of the original rate to lower losses to the same level as when clippings were removed. The fertilization rate for the extension service schedules must be lowered to about half its original rate to reduce nitrogen losses to the levels when clippings are removed.

Phosphorus Losses and the Effect of Slope on Nutrient Losses in Runoff

A series of simulations were performed to determine the effect of slope on nutrient losses in runoff. Turfgrass was represented on slopes of 2%, 5%, and 10% for all of the soils simulated from hydrologic groups B and C. Hydrologic group A produces little runoff.

A second purpose in performing these simulations was to quantify phosphorus losses from turfgrass. On healthy turf, little erosion can be expected to occur. The primary avenue for phosphorus losses is in runoff. The simulations were run at two different levels of phosphorus concentrations in soil, 40 ppm and 400 ppm. No additional phosphorus was added in fertilizer. Nitrogen fertilizer was applied according to the fertilization schedules modeled in the previous simulations.

The Effect of Slope on Runoff

Table 9 shows the average annual runoff from the hydrologic group B and C soils as a function of slope. Soil type is more significant in determining runoff than slope. For the group B soils, the Glenelg silt loam and the Pamunkey fine sand loam, average annual runoff is less than 2.5 inches, regardless of slope. Over the range of slopes, from 2% to 10%, average annual runoff varies by about one inch. On the other hand, on the group C soils, the Elioak loam and the Caroline fine

Table 9

Average Annual Runoff (in)

As a Function of Slope

Soil	2% Slope	5% Slope	10% Slope
Glenelg silt loam	1.0	1.3	1.7
Elioak loam	3.6	4.3	5.2
Pamunkey fine sandy loam	1.3	1.7	2.3
Caroline fine sandy loam	5.8	6.8	7.9

sandy loam, average annual runoff is no less than 3.5 in/yr. Over the range of slopes, average annual runoff varies on the Elioak soil from 3.6 in to 5.2 inches, and on the Caroline soil from 5.8 in/yr to 7.9 in/yr.

Nitrogen Losses in Runoff as A Function of Slope

Table 10 shows the average annual nitrogen losses in runoff as a function of slope. As was the case with runoff itself, soil type is the biggest factor in determining nitrogen losses. On average,

Table 10

Average Annual Nitrogen Losses (lb/ac)

As a Function of Slope

Scenario	2% Slope	5% Slope	10% Slope
	Glenelg Silt Loam		
Lawn Service I	0.8	1.1	1.5
Lawn Service II	0.8	1.2	1.7
Four-Step	0.5	0.8	1.2
Extension Service I	0.4	0.7	1.0
Extension Service II	0.5	0.8	1.1
Extension Service III	0.6	1.0	1.4
	Elioak Loam		
Lawn Service I	3.6	5.0	6.9
Lawn Service II	4.5	6.1	8.1
Four-Step	3.7	4.9	6.5
Extension Service I	2.9	3.8	5.0
Extension Service II	3.2	4.1	5.3
Extension Service III	4.3	5.8	7.8

Scenario	2% Slope	5% Slope	10% Slope
	Pamunkey Fine Sandy Loam		
Lawn Service I	1.2	1.8	2.7
Lawn Service II	1.3	1.2	2.0
Four-Step	0.8	1.2	1.8
Extension Service IV	0.7	1.0	1.4
Extension Service V	1.1	1.6	2.3
	Caroline Fine Sandy Loam		
Lawn Service I	9.3	12.2	16.0
Lawn Service II	8.3	11.2	14.9
Four-Step	6.3	8.3	11.1
Extension Service IV	4.5	5.7	7.4
Extension Service V	7.7	9.8	12.5

no more than two pounds of nitrogen in lost in runoff each year on the Glenelg soil and no more than three pounds of nitrogen is lost on the Pamunkey soil, over all slopes and fertilization schedules. In contrast to these group B soils, the losses from group C soils are more significant. Average annual losses in the Elioak soil are never less than about three pounds, and average annual losses on the Caroline soil are never less than four pounds. On the Elioak loam, average annual nitrogen losses in runoff are as high as 8.1 lb/ac when the Lawn Service II schedule is used on a 10% slope. On the Caroline soil, losses are as high as 16.0 lb/ac when the Lawn Service I schedule is used on a 10% slope.

For a given soil, slope can have as large an effect in determining nitrogen losses in runoff as the fertilization schedule. On the Glenelg silt loam, for example, with a 2% slope, average annual losses range from 0.4 lb/ac to 0.8 lb/ac over the fertilization schedules. In contrast, over the range of slopes, losses from the Lawn Service I schedule range from 0.8 lb/ac to 1.5 lb/ac and losses from the Extension Service I schedule range from 0.4 lb/ac to 1.1 lb/ac. Similarly, on the Elioak soil on a 10% slope, average annual losses range from 5.0 lb/ac to 8.1 lb/ac, while losses from Lawn Service II range from 4.5 lb/ac on a 2% slope to 8.1 lb/ac on a 10% slope. Thus a large difference in slope could have as much impact as the fertilization schedule.

The fertilization schedules, however, do have an effect on the amount of runoff losses. For cool-season grass, the Extension Service I schedule consistently has the lowest losses, followed closely by Extension Service II. For warm-season grass, Extension IV has the lowest losses, followed by the Four-Step schedule. Lawn Service II has the highest losses on cool-season grass, and Lawn Service I generally has the highest losses on warm-season grass. Although the rate of nitrogen application is the largest factor in determining nitrogen losses in runoff, the timing of the applications has some effect on losses, and can affect different soils or grass types differently. Lawn Service I has the highest nitrogen application rate, and generally has high losses, but on the Elioak loam, losses from Lawn Service I are moderate.

Phosphorus Losses in Runoff

Table 11 shows the average annual phosphorus losses in runoff. Losses are given for the simulations that apply nitrogen according to the Lawn Service I schedule. There is a small variation in phosphorus losses with fertilization schedule due the differences in turfgrass growth, even though no phosphorus is applied as fertilizer.

Table 11

Average Annual Phosphorus Losses in Runoff (lb/ac)

At 2%, 5%, and 10% Slope

No Irrigation--Clippings Removed

	Low Soil Phosphorus (40 ppm)			High Soil Phosphorus (400 ppm)		
Soil	2%	5%	10%	2%	5%	10%
Glenelg silt loam	0.01	0.01	0.01	0.10	0.14	0.18
Elioak loam	0.03	0.04	0.05	0.43	0.53	0.64
Pamunkey fine sandy loam	0.01	0.01	0.02	0.12	0.17	0.23
Caroline fine sandy loam	0.03	0.04	0.04	0.51	0.62	0.75

When the concentration of phosphorus in the soil is low, phosphorus losses in runoff are insignificant, regardless of soil type. When the concentration of phosphorus in the soil is 400 ppm, losses are more significant, but never amount to more than 1.0 lb/ac/yr on average. On the group B soils, average annual phosphorus losses are never more than 0.25 lb/ac, regardless of slope. Losses are generally above 0.5 lb/ac/yr on the group C soils, where more runoff occurs. There is about a 50% increase in losses on the group C soils over the range of slope simulated. Losses on the Elioak soil generally range from 0.43 lb/ac/yr to 0.64 lb/ac/yr, and losses in the Caroline soil range from 0.51 lb/ac/yr to 0.75 lb/ac/yr.

There were no seasonal trends in the phosphorus losses in runoff. Losses occurred fairly evenly throughout the year. Average monthly phosphorus losses in runoff were also not correlated with average monthly runoff.

Phosphorus Losses in Percolation

EPIC does represent phosphorus losses in percolation. The model of phosphorus transport in percolation which EPIC uses is simple. EPIC does not represent sorption of phosphate by the soil. Rather, it is assumed that labile phosphorus is partitioned between the soil and water phases in proportion to the mass of the soil and water phases in the soil layer. The concentration of phosphorus in the soil water can then be determined, and the quantity of phosphorus transported in percolation is determined on the basis of the quantity of phosphorus in the soil water. In the absence of any way of predicting the phosphate sorption capacity of the soil on the basis of soil properties, this method is as good as any. It has the virtue that phosphorus losses are sensitive to the amount of percolation and the concentration of phosphorus in the soil. Nevertheless, this method is less sophisticated than the other aspects of EPIC's representation of the nutrient cycle.

For the sake of completeness, average annual phosphorus losses in percolation are reported in Table 12 for the simulations with a 5% slope. These results should be used with the appropriate caution. They suggest that about 1 lb/ac
of phosphorus is lost in percolation annually when the concentration of phosphorus in the top soil

layers is 400 ppm. These losses are higher than the losses in runoff. At low soil phosphorus concentrations, losses in percolation are considerably less.

Table 12

Average Annual Phosphorus Losses in Percolation (lb/ac)

Soil	Low Soil Phosphorus (40 ppm)	High Soil Phosphorus (400 ppm)
Glenelg silt loam	0.23	1.00
Elioak loam	0.21	0.87
Pamunkey fine sandy loam	0.27	1.31
Caroline fine sandy loam	0.11	1.06

Summary of Effects of Fertilizer Schedule, Management Practices, and Soil Type on Nitrogen Losses

Figures 1 through 6 show total average annual nitrogen losses for each of the soils simulated in this study: Glenelg silt loam, Galestown sand, Elioak loam, Pamunky fine sandy loam, Buncombe loamy sand, and Caroline fine sandy loam. Each figure shows the losses associated with fertilizer schedules for each of the three management scenarios simulated: clippings removed with no irrigation, clippings removed with irrigation, and clippings returned with irrigation. The results are summarized below.

Fertilizer schedules. The effects of fertilizer schedules on nitrogen losses are remarkably consistent across management scenarios and soil types. For cool-season grass, the Extension Service II had the lowest losses, regardless of management scenario or soil type, for all simulations except one. The nitrogen losses from Extension Service I were higher but comparable in size to those for Extension Service II. Lawn Service I and II, and Extension Service III had the highest losses. Losses from the Four-Step schedule fell between these two groups. The rate of application primarily determines nitrogen losses. Extension Service I and II apply 3 lb/1000 ft of nitrogen per year, the Four-Step schedule 3.6 lb/1000 ft/yr, and other schedules apply 4.5-5.0 lb/1000 ft/yr. Timing, however, also has an effect. Losses from Extension Service II are consistently several pounds less than those from Extension Service I. These two schedules differ only in that Extension Service I applies 1.0 lb/1000 ft/yr on December 10 and Extension II applies the same amount on November 10, when the grass is still able to use some of the nitrogen. Lawn Service I usually has lower losses than either Lawn Service II or Extension Service III, even though it has the highest application rate of any of the fertilizer schedules, because it applies more of its nitrogen during the growing season.

For warm-season grass, the Extension Service IV schedule produces the lowest nitrogen losses for every management scenario and every soil type. The lawn service schedules produce the largest losses. Losses for the Extension V and Four-Step schedules fall between the losses from the lawn service schedules and Extension Service IV. Rate is once more the primary factor in

Figure 2

Total Average Annual Nitrogen Losses (lb/ac)

Cool-Season Grass on Galestown Sand

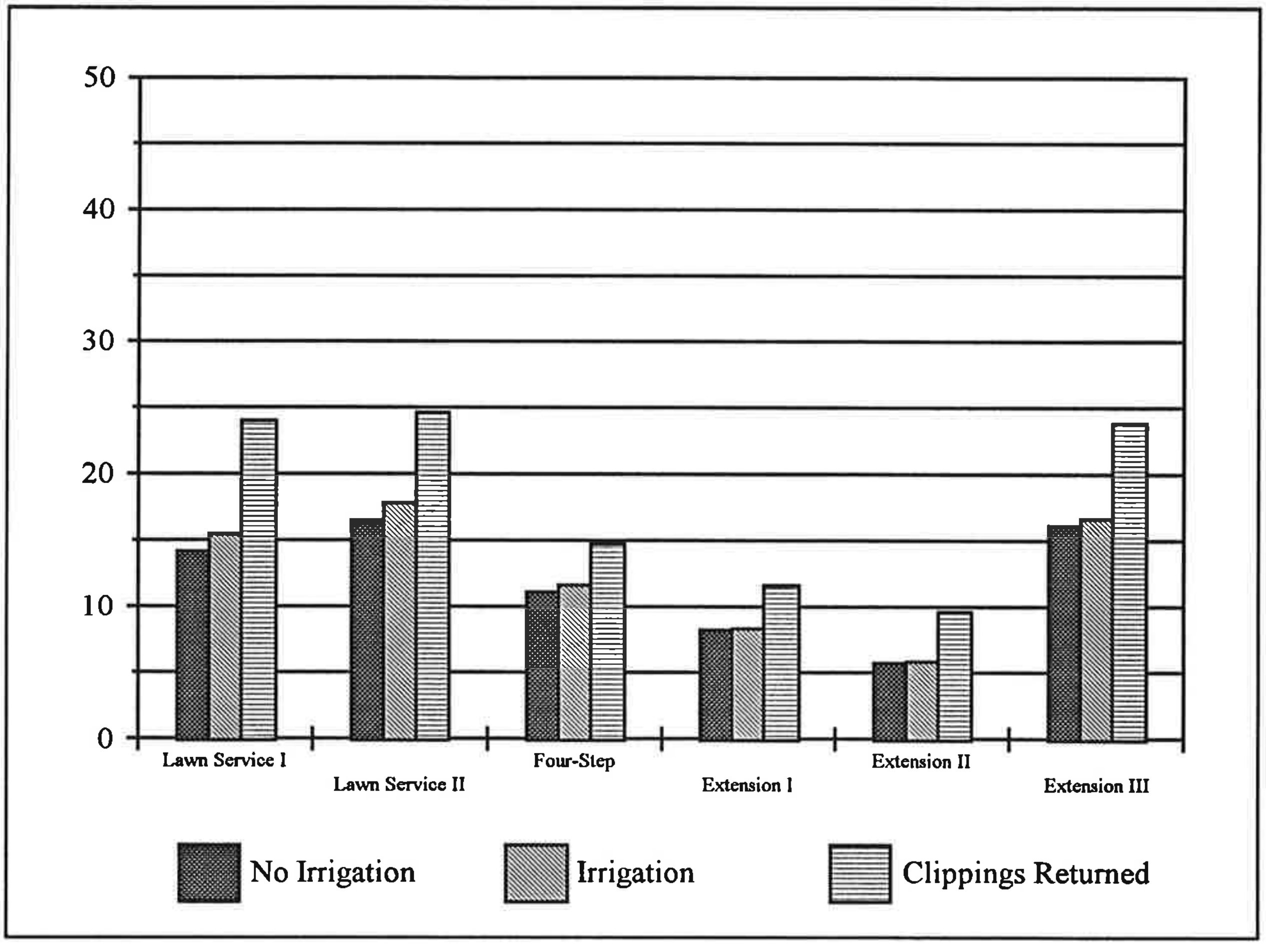


Figure 3

Total Average Annual Nitrogen Losses (lb/ac)

Cool-Season Grass on Elioak Loam

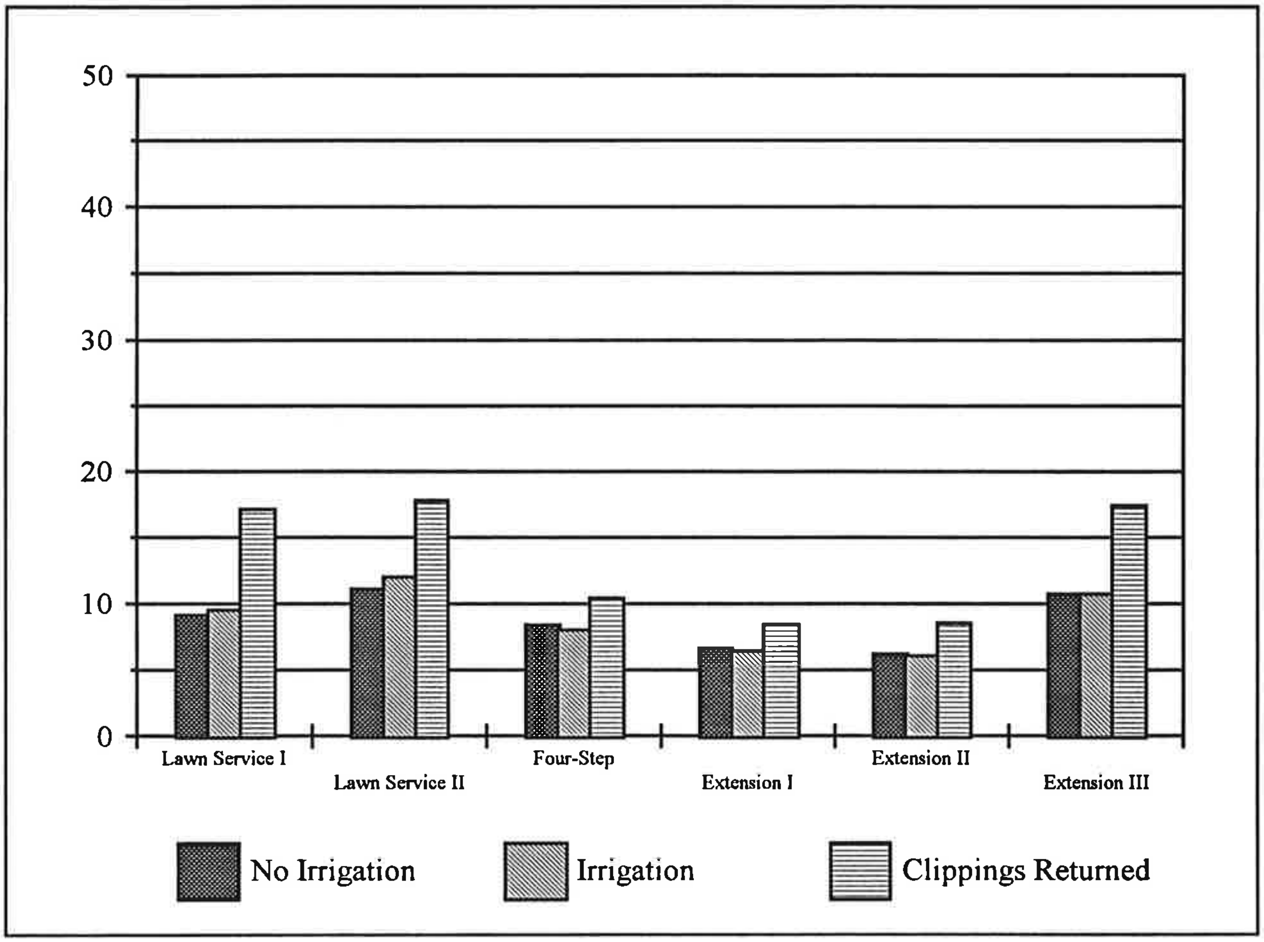


Figure 4

Total Average Annual Nitrogen Losses (lb/ac)

Warm-Season Grass on Pamunkey Fine Sandy Loam

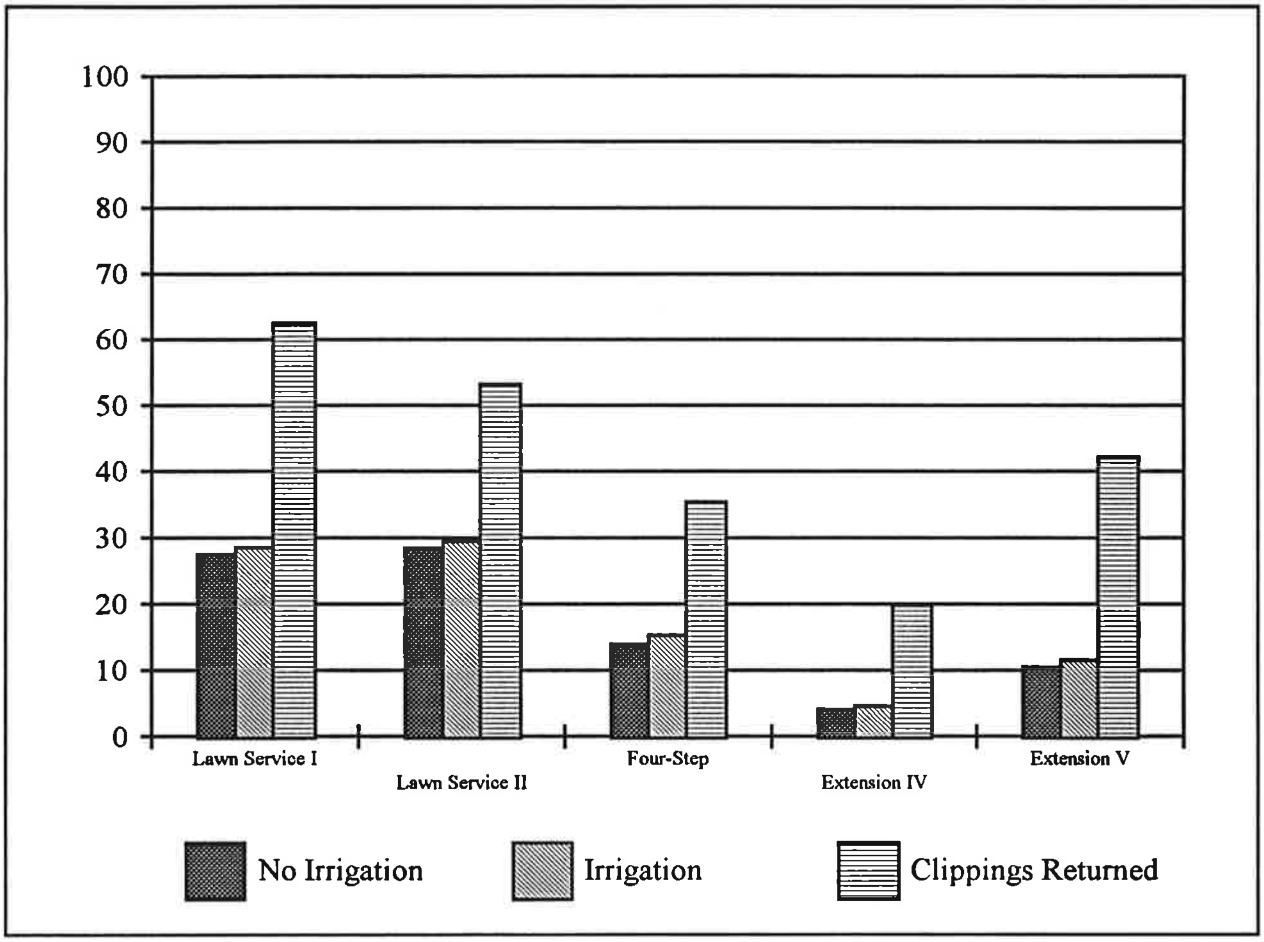


Figure 5

Total Average Annual Nitrogen Losses (lb/ac)

Warm-Season Grass on Buncombe Loamy Sand

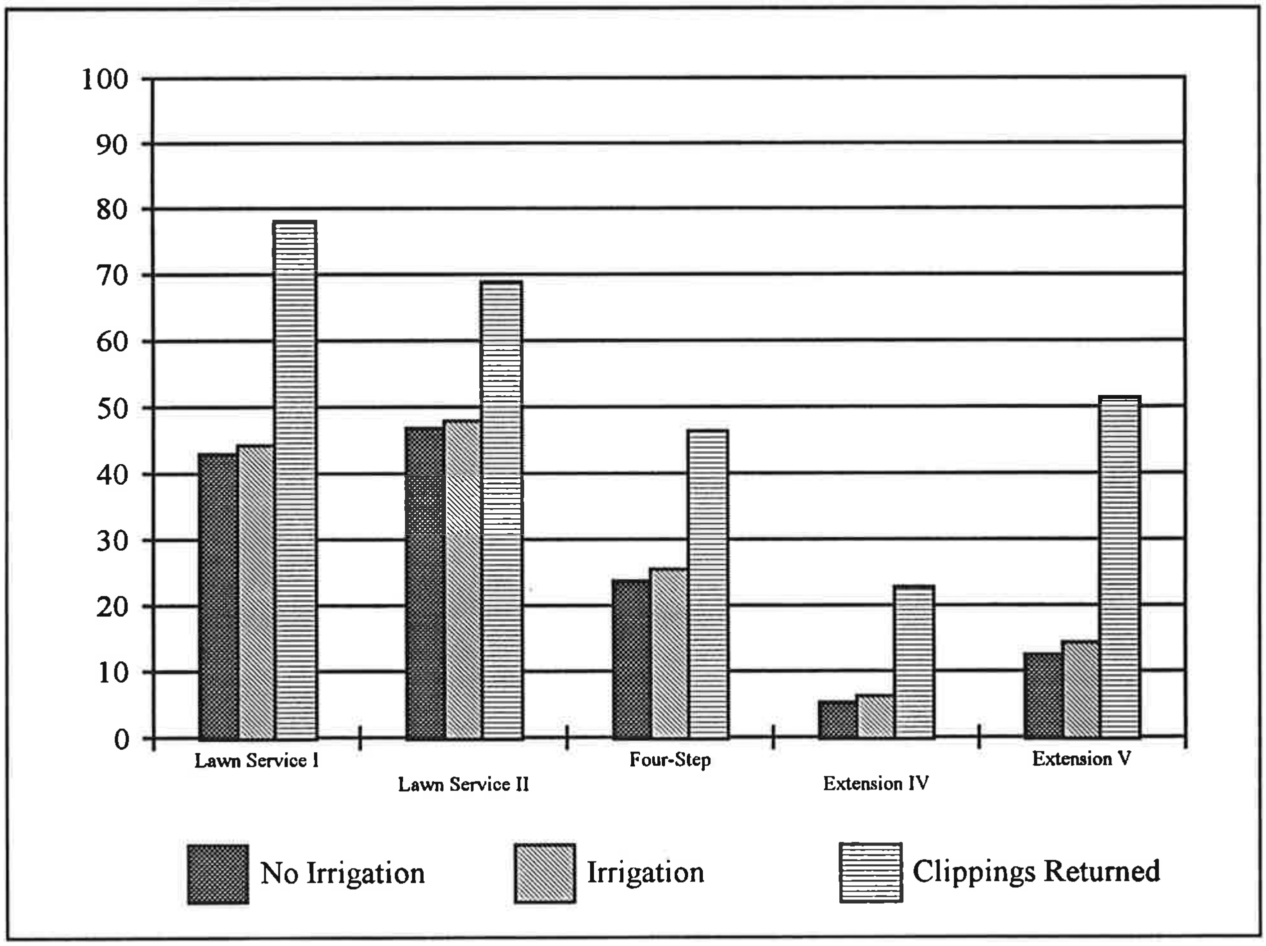
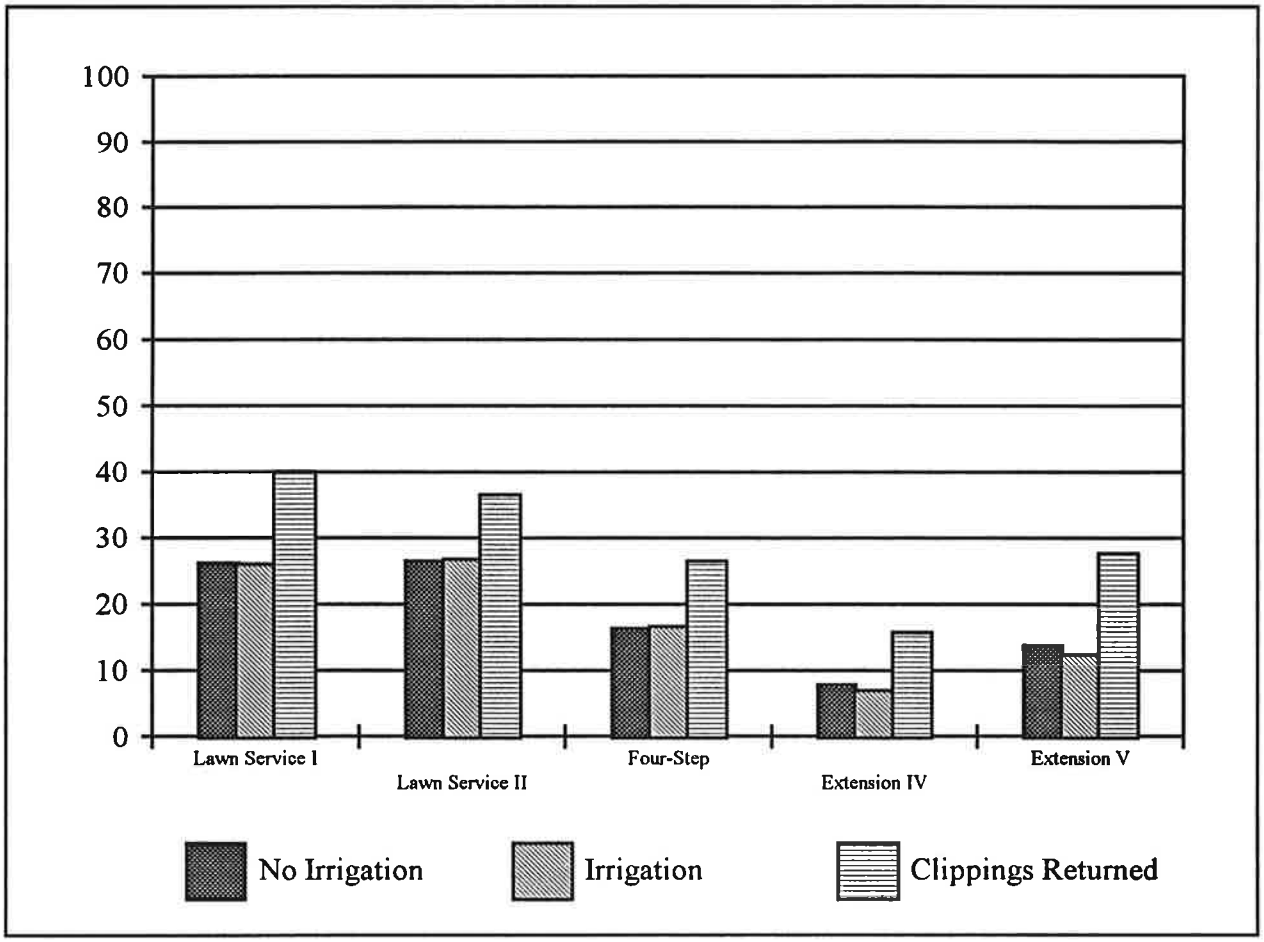


Figure 6

Total Average Annual Nitrogen Losses (lb/ac)

Warm-Season Grass on Caroline Fine Sandy Loam



determining nitrogen losses. Extension Service IV applies only 3 lb/1000 ft/yr, while Extension V applies 4 lb/1000 ft/yr. Timing is also important. The low losses for Extension IV are attributable not only to the lower rate of application, but also to the fact that the nitrogen is applied just before and during the growing season.

To illustrate these points, simulations were performed using the lawn service schedules, but reducing their application rate to 3 lb/ac/yr by proportionately reducing all of their applications. The number of applications remained the same, but each application was reduced by 40%, in the case of Lawn Service I, and 34%, in the case of Lawn Service II. These reduced lawn service schedules were applied on each soil. Summary statistics for these simulations are given in Tables A.118 through A.129. The results show that on cool-season grass, reducing the application rate in the Lawn Service I schedule reduced total average annual nitrogen losses by 53%, 56%, and 47%, on the Glenelg, Galestown, and Elioak soils, respectively. These losses were comparable to the low losses that occur when the Extension II schedule is used. Losses from using the Lawn Service II schedule with reduced application rates were reduced by 45%, 44%, and 38%, respectively. These losses were somewhat higher than the losses from the reduced Lawn Service I simulations, but on all soils total average annual nitrogen losses were less than 10 lb/ac.

For warm-season grass, the Lawn Service I schedule with reduced nitrogen application rates reduced losses by 51%, 42%, and 43%, on the Pamunkey, Buncombe, and Caroline soils, respectively, while the adjusted Lawn Service II schedule reduced losses on these soils by 39%, 38%, and 35%, respectively. Total average annual nitrogen losses remained above 10 lb/ac for all soils. Losses for the adjusted lawn service schedules are still considerably higher than the losses in simulations using Extension Service IV, which also applies 3 lb/ 1000 ft/yr of nitrogen, because of the timing of the applications. Extension Service IV applies nitrogen either just before the growing season, in April, or during the growing season, whereas the lawn service schedules apply nitrogen in the late fall and early spring, long before it can be used by the grass. For both cool-season grass and warm-season grass, there is a drop in nitrogen uptake as a result of the reduction in nitrogen applied in fertilizer. On cool-season grass, nitrogen uptake is reduced to about 10 lb/ac/yr below the level of uptake when Extension Service II is used, while on warm-season grass, uptake drops to 20-35 lb/ac/yr below the level of uptake when Extension IV, indicating that the schedule of the lawn service schedules is not as efficient in delivering nitrogen to warm-season grass as the Extension Service IV schedule.

Soil type. The soils from hydrologic group C, the Elioak loam and the Caroline fine sandy loam, behave differently than the other soils, which come from hydrologic groups A and B. Nitrogen losses in runoff are substantial from the group C soils, and equal or outweigh percolation losses except when clippings are returned to the turf. Because there is less percolation from C soils, there are less nitrogen losses in percolation on these soils than on the A or B soils. This leads to slightly less total nitrogen losses overall. The relative effect of fertilizer schedules on the C soils is the same as for the A and B soils, because the rate of nitrogen application is the primary factor determining nitrogen losses. Timing has its affects. Extension Service I has less nitrogen losses in runoff than Extension Service II, because Extension Service II has a fertilizer application in November, a month with significant runoff. On the Elioak soil, when clippings are returned to the turf, total average annual nitrogen losses are 0.1 lb/ac higher for the Extension Service II schedule than the Extension I schedule--the only simulation where the losses from the Extension Service II schedule are greater than the losses from Extension Service I.

The A soils tend to have higher percolation rates, and higher nitrogen losses in percolation, than the B soils, when the same fertilizer schedule is used. When there is no irrigation, the increase in total nitrogen losses ranges from 5-15% for cool-season grass and 19-71% for warm-season grass. Schedules with higher losses tend to have a greater increase in losses when the losses from A soils are compared to the losses from B soils.

Management practices. Irrigating turf does lead to greater percolation and greater nitrogen losses in percolation, but the increase in losses caused by percolation is small for most soils and most fertilization schedules. The increase in losses ranges between 7 and 9% on the Glenelg and Galestown soils when the lawn service schedules are used, and between 8% and 17% on the

Pamunkey and Buncombe soils when the extension service schedules or the four-step program are used. Otherwise the increase in losses is less than 5%. Losses actually decrease when the extension service schedules are used on the group C soils, because irrigation leaches nitrogen out of the surface soil layer, decreasing nitrogen losses in runoff.

Returning the clippings to the lawn more dramatically increases nitrogen losses. For cool-season grass, the increase in losses ranges from 27% to 80%. The increase in losses on warm-season grass is over 100% on the Pamunkey soil and for all simulations using the extension service schedules, though it should be noted that losses are initially low when the extension service schedules are used. On the Buncombe and Caroline soils for other schedules, the increase in losses ranges from 37% to 82%.

Returning clippings to the lawn recycles the nitrogen which the grass previously removed from the soil. Less nitrogen in fertilizer is needed to maintain growth. If the amount of nitrogen applied in fertilizer is decreased, nitrogen losses can be reduced to the same level which occurs when the turfgrass is irrigated but the clippings removed. For cool-season grass, the nitrogen applied in fertilizer should be reduced by about 20%. For warm season grass, the nitrogen applied in fertilizer should be reduced by about half for the extension service schedules and by about 30-35% on the other schedules, to return nitrogen losses to the levels the occur when clippings are removed.

Grass type. Warm-season grass tends to have higher nitrogen losses than cool-season grass. The higher losses from warm-season grass stem from its shorter growing season and its more limited capacity to take up nitrogen during the growing season. The use of the Extension Service IV schedule demonstrates that nitrogen losses from warm-season grass can be kept as low as losses from cool-season grass by proper timing and application rate.

Suggestions For Reducing Nitrogen Losses From Turfgrass

The results from these simulations suggest several steps could be taken to reduce nitrogen losses from turfgrass. The following suggestions could be implemented without radically changing current turfgrass management practices:

- For cool-season grass, minimize fertilizer applications that occur in late fall, winter, or early spring while the grass is not removing nitrogen from the soil.
- Lawn service companies could reduce application rates on cool-season grass.
- On warm-season grass, the rate and timing of nitrogen application should be adjusted to take into account the shorter growing season and more limited nitrogen uptake of warm-season grass.
- Nitrogen application rates should be reduced on all fertilizer schedules if clippings are returned to the lawn.

If these measure are taken, the use of fertilizer on home lawns does not have to lead to excess nutrients reaching ground water and surface water where they can cause environmental problems. The proper rate and timing of nitrogen fertilizer application can minimize the potential impacts of the use fertilizer on home lawns.

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