ANNUAL PROGRESS REPORT

Evaluation of Best Management Practices to Protect Surface Water Quality from Pesticides and Fertilizer Applied to Bermudagrass Fairways

For the Period

1 November 1995 - 31 October 1996

Submitted By

J. H. Baird
Turfgrass Science

J. T. Cole
Environmental Sciences Graduate Assistant

R. L. Huhnke
Agricultural Engineering

N. T. Basta
Soil Chemistry

M. E. Payton
Statistics

G. V. Johnson
Soil Fertility

D. E. Storm
Water Resources Engineering

M. D. Smolen
Water Quality

JOINTLY SPONSORED BY THE
UNITED STATES GOLF ASSOCIATION
AND
OKLAHOMA AGRICULTURAL EXPERIMENT STATION
OKLAHOMA STATE UNIVERSITY

EXECUTIVE SUMMARY

This project represents a team effort of scientists in turfgrass science, soil fertility and chemistry, engineering, water quality, and statistics aimed at developing effective and practical management practices to protect surface water from runoff of pesticides and fertilizer applied to golf course bermudagrass fairways and other turf areas.

In 1995, research was conducted to evaluate the influence of buffer-strip length, height, and aerification on pesticide and nutrient runoff from bermudagrass turf. A manuscript describing the research was submitted to the Journal of Environmental Quality in September 1996.

In 1996, two experiments were conducted to further examine the effects of buffer-strip mowing height and buffer-strip length on pesticide and nutrient runoff from bermudagrass (*Cynodon dactylon* L. Pers.) turf on a Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls) on a 6% slope. In the mowing height experiment, treatments evaluated were buffer-strips (6-ft width x 16-ft length) mowed at 0.5, 1.5, and 3.0 in. In addition, a buffer-strip mowed at 1.5 in was used as an untreated control to determine antecedent nutrient levels. In the length experiment, treatments evaluated were buffer-strips (6-ft width) measuring 0, 4, 8, and 16 ft in length and mowed at 1.5 in. In both experiments, the area receiving pesticides and fertilizer (6-ft width x 16-ft length) was located upslope from the buffer and was mowed at 0.5 in. Urea (applied in mowing height experiment), sulfur-coated urea (SCU) (applied in the buffer-strip length experiment), triple superphosphate, chlorpyrifos [granular (applied in the mowing height experiment) or wettable powder (applied in the length experiment)], and the dimethylamine salts of 2,4-D, mecoprop, and dicamba were applied at recommended rates to each experiment. A portable rainfall simulator was used to apply a precipitation rate of 2.5 in/h for 75 min within 24 h after chemical application.

Chlorpyrifos recoveries in the 1996 runoff samples were much lower than found in 1995; consequently, chlorpyrifos data were not presented and the runoff samples will be reanalyzed using an enzyme-linked immunosorbant assay (ELISA) specific for detection of the insecticide.

In the mowing height experiment, the 3.0-in buffer was most effective in delaying time to start of runoff and decreasing total runoff volume. Pesticide and nutrient losses to surface runoff were as great as 11% and 10%, respectively, from the 1.5-in mowing height treatment. Overall, there appeared to be no advantage in mowing the buffer-strip either 0.5- or 1.5-in in terms of reducing pesticide and nutrient runoff. Although not statistically significant, the 3.0-in buffer-strip mowing height was most effective in reducing pesticide nutrient runoff in July compared to the other treatments. However, in August, pesticide and nutrient recoveries in runoff water from the 3.0-in buffer-strip treatment were as great as the other treatments. The positive effect of the 3.0-in buffer was most likely overcome

by higher soil moisture conditions and subsequent surface runoff of water in August compared to July.

Pesticide and nutrient loss to surface runoff was less than 7% in the buffer-strip length experiment. The differences in surface runoff losses between the two experiments were most likely due to differences in soil moisture caused by experiment location; the buffer-strip length study was positioned on the drier upslope from the mowing height study. Overall, data from this experiment reaffirmed that buffer-strips are effective in reducing pesticide and nutrient runoff. In addition, these data may be very useful for extrapolating effective buffer-strip lengths for testing on larger scale watersheds.

Reduction in loss of nitrogen in surface runoff occurred from SCU applied in the buffer-strip length study compared to urea applied in the buffer-strip mowing height study; however, these results may have been caused by differences in soil moisture between experiment locations.

Similar to 1995, results of the 1996 experiments confirm that use of buffer-strips, use of pesticides and fertilizers with lower water solubilities, and avoidance of pesticide and nutrient application when soil is saturated help reduce chemical loss in surface runoff from turf.

INTRODUCTION

The potential for runoff of pesticides and nutrients from turf, especially on golf courses, into surface water is the subject of increasing environmental concern. As a result, a project was initiated in 1995 under the joint sponsorship of the United States Golf Association and the Oklahoma Agricultural Experiment Station. The primary objective was to evaluate and develop management strategies that are both practical and effective in reducing pesticide and nutrient runoff from golf courses and other turf.

RESEARCH PROGRESS

1995 Research

A manuscript describing research conducted in 1995 was submitted to the Journal of Environmental Quality in September 1996 and is included in Appendix 1.

1996 Research

Methods

General research methodology for both experiments is described in Appendix 1.

Influence of Buffer-Strip Mowing Height on Pesticide and Nutrient Runoff from Bermudagrass Turf. Treatments evaluated were buffer-strips (6-ft wide x 16-ft length) mowed at 0.5, 1.5, and 3.0 in. In addition, a buffer-strip mowed at 1.5 in was used as an untreated control to determine antecedent nutrient levels. The treated area (6-ft wide x 16-ft length) was located upslope from the buffer and was mowed at 0.5 in. The following fertilizers and pesticides were applied to the treated area: nitrogen at 1 lb N/1000 ft^2 from urea (46N-0P-0K); phosphorus at 1 lb P/1000 ft^2 from triple superphosphate (0N-20P-0K); chlorpyrifos 0.5 G at 2.0 lb ai/A; and 2,4-D at 1.0 lb ai/A, mecoprop at 0.5 lb ai/A, and dicamba at 0.1 lb ai/A formulated as dimethylamine salts in Trimec® Classic herbicide. Fertilizer and insecticide were applied and irrigated with 0.2 in of water using the rainfall simulator calibrated to deliver 2.5 in/h. The herbicides were subsequently applied after the wetted turf had dried using a CO_2-powered ground sprayer set to deliver 20 gallons/A of water. Simulated rainfall was applied within 24 h of application of pesticides and nutrients. Rainfall intensity was set at 2.5 in/h for 75 min.

Influence of Buffer-Strip Length on Pesticide and Nutrient Runoff from Turf. Treatments evaluated were buffer-strips (6-ft wide) measuring 0, 4, 8, and 16 ft in length. The buffers were mowed at 1.5 in. Pesticide and nutrient application was identical to the mowing height study except that the 50 WP formulation of chlorpyrifos and a sulfur-coated urea (SCU) (39N-0P-0K) formulation of nitrogen were used instead of the granular chlorpyrifos and urea nitrogen formulations, respectively.

Both experiments utilized a randomized complete block design and each treatment was replicated four times. Data were subjected to analysis of covariance (ANCOVA). The time to the start of runoff and total runoff volume for each plot were used as covariates in the analyses of concentration and mass, respectively, in order to account for differences in runoff that were due to differences in antecedent soil moisture or natural variation in soil properties. Both experiments were initiated in July 1996 and repeated in August 1996.

Results

Chlorpyrifos recoveries in the 1996 runoff samples were much lower than found in 1995; consequently, chlorpyrifos data are not shown and the runoff samples will be reanalyzed using an enzyme-linked immunosorbant assay (ELISA) specific for detection of the insecticide.

Influence of Buffer-Strip Mowing Height on Pesticide and Nutrient Runoff from Bermudagrass Turf. Time to start of runoff and total runoff volume data for July and August are shown in Tables 1 and 2, respectively. The 1.5-in buffer increased the time to start of runoff compared to the 0.5-in buffer but did not decrease total runoff volume. The 3.0-in buffer was most effective in increasing time to start of runoff and decreasing total runoff volume. These results support field observations made during the simulated rainfall events of a dam-effect present at intersection of the 0.5-in treated area and 3.0-in buffer-strip canopies. Concentration and mass of pesticides and nutrients recovered in runoff are presented in Tables 3-6. Pesticide and nutrient loss to surface runoff was as great as 11% and 10%, respectively, from the 1.5-in mowing height (Tables 7 and 8). Pesticide and nutrient concentration and mass values adjusted for the covariates are reported as least squares means in Tables 9-12. Overall, these data suggest the following: 1) there appears to be no advantage in using either 0.5- or 1.5-in mowing heights in a buffer-strip to reduce pesticide and nutrient runoff; and 2) although not statistically significant, the 3.0-in buffer-strip mowing height was most effective in reducing pesticide nutrient runoff in July compared to the other treatments. However, in August, pesticide and nutrient recoveries in runoff water from the 3.0-in buffer-strip treatment were as great as the other treatments most likely due to increased soil saturation and surface runoff of water in August compared to July.

Influence of Buffer-Strip Length on Pesticide and Nutrient Runoff from Turf. Time to start of runoff and total runoff volume data for July and August are shown in Tables 13 and 14, respectively. Compared to the treatment containing no buffer, the 16-ft buffer-strip treatment contained twice as much surface area to receive precipitation; consequently, almost twice as much runoff left the 16-ft buffer treatment. Concentration and mass of pesticides and nutrients recovered in runoff are presented in Tables 15-18. Pesticide and nutrient loss to surface runoff was less than 7% (Tables 19 and 20). Pesticide and nutrient concentration and mass values adjusted for the covariates are reported as least squares means in Tables 21-24. Overall, these data suggest the following: 1) buffer-strips are effective in reducing pesticide and nutrient runoff; and 2) data from this experiment may be very useful for extrapolating effective buffer-strip lengths for testing on larger scale watersheds.

Overall, reduced loss of nitrogen in surface runoff occurred from SCU applied in the buffer-strip length study compared to urea applied in the buffer-strip mowing height study (Tables 3-6 and 15-18). However, these results may have been caused by differences in soil moisture between experimental locations.

RESEARCH PLANNED

Having used the portable rainfall simulator to obtain basic information on strategies to reduce pesticide and nutrient runoff from bermudagrass turf, our next step is to test our findings on larger scale plots which more closely simulate conditions on the golf course. This winter, a permanent runoff facility will be constructed at the OSU Turfgrass Research Center in Stillwater. The facility will consist of 3-6 runoff plots each 0.25-0.5 acres in area. Collection flumes and autosampling devices will be constructed or purchased for each plot location. A subsurface, head-to-head irrigation system will be installed to supply precipitation required for runoff. Upon final construction, the plots will be sodded with bermudagrass and possibly other turfgrass species to be ready for 1997 experiments. Next year we plan to further focus on determining effective buffer-strip lengths and vegetation heights for reducing surface runoff of pesticides and nutrients from larger watersheds.

This facility will allow us to further test and demonstrate the effectiveness and practicality of management practices aimed toward reducing pesticide and nutrient runoff from golf course turf. As a result, golf course superintendents and golfers are more likely to embrace and utilize these strategies to protect the environment.

Table 1. Time to start of runoff and total runoff water for buffer-strip mowing height treatments in the July 1996 simulated rainfall event.

Mowing	Time to Start of Runoff		Runoff Volume	
Height	Mean	SD	Mean	SD
(in)	(min)	(min)	(L)	(L)
0.5	7	4	733	121
1.5	16	7	731	151
1.5*	16	4	705	259
3	24	9	433	298

*Untreated Control.

Table 2. Time to start of runoff and total runoff water for buffer-strip mowing height treatments in the August 1996 simulated rainfall event.

Mowing	Time to Start of Runoff		Runoff Volume	
Height	Mean	SD	Mean	SD
(in)	(min)	(min)	(L)	(L)
0.5	8	5	896	178
1.5	12	3	915	130
1.5*	15	5	706	236
3	19	5	614	329

*Untreated Control.

Table 3. Effect of buffer-strip mowing height on concentration of pesticides and nutrients recovered in runoff water in July 1996.

Mowing Height	Pesticide Concentration			Nutrient Concentration		
	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0.5	6.25	71.5	36.5	1.70	0.820	3.63
1.5	6.50	82.0	41.5	2.05	1.06	4.24
1.5*	0	0	0	1.12	1.04	0.362
3	3.25	36.3	25.5	1.36	0.958	1.54

Table 4. Effect of buffer-strip mowing height on concentration of pesticides and nutrients recovered in runoff water in August 1996.

Mowing Height	Pesticide Concentration			Nutrient Concentration		
	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0.5	7.50	95.5	46.0	0.995	0.873	5.72
1.5	8.75	118	53.5	1.44	1.20	6.72
1.5*	0	0	0	0.216	1.07	1.94
3	8.25	93.5	44.5	0.903	1.17	5.23

Table 5. Effect of buffer-strip mowing height on mass of pesticides and nutrients recovered in runoff water in July 1996.

Mowing Height	Pesticide Mass			Nutrient Mass		
	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0.5	4660	54600	27500	1240	596	2800
1.5	5000	63700	31900	1550	808	3440
1.5*	0	0	0	787	746	256
3	1590	13100	12000	584	416	720

Table 6. Effect of buffer-strip mowing height on mass of pesticides and nutrients recovered in runoff water in August 1996.

Mowing Height	Pesticide Mass			Nutrient Mass		
	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0.5	6930	88600	42400	883	779	5180
1.5	8170	110000	49800	1350	1110	6280
1.5*	0	0	0	142	767	1780
3	5570	60500	28700	534	704	3590

*Untreated Control.

** Source of applied N = urea.

Table 7. Recovery of pesticides and nutrients in the July 1996 buffer-strip mowing height study.

Mowing Height	Recovery in Runoff Water					
	Dicamba	2,4-D	Mecoprop	NH_4-N#	NO_3-N#	PO_4
(in)	(%**)	(%)	(%)	(%)	(%)	(%)
0.5	4.2	5.5	5.1	1.0	-0.3	5.8
1.5	4.6	6.4	5.9	1.7	0.1	7.2
1.5*	0	0	0	***	***	***
3	1.5	1.3	2.2	-0.5	-0.8	1.1

Table 8. Recovery of pesticides and nutrients in the August 1996 buffer-strip mowing height study.

Mowing Height	Recovery in Runoff Water					
	Dicamba	2,4-D	Mecoprop	NH_4-N#	NO_3-N#	PO_4
(in)	(%)	(%)	(%)	(%)	(%)	(%)
0.5	6.3	8.9	7.9	1.7	0.03	7.7
1.5	7.4	11	9.2	2.7	0.8	10
1.5*	0	0	0.3	***	***	***
3	5.1	6.1	5.3	0.9	-0.1	4.1

*Untreated Control.

**Percentage of applied pesticide or nutrient recovered in runoff water.

***Nutrient recovery adjusted for nutrients recovered in runoff water from untreated control.

#Source of applied N = urea.

Table 9. Least squares means for effect of buffer-strip mowing height on concentration of pesticides and nutrients recovered in runoff water in July 1996.

Mowing	Pesticide Concentration			Nutrient Concentration		
Height	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0.5	5.93 a	73.8 a	33.3 a	1.71 a	0.782 a	3.20 ab
1.5	6.50 a	82.0 a	41.5 a	2.05 a	1.06 a	4.24 a
1.5*	0.018 b	-0.127 b	0.175 b	1.12 b	1.04 a	0.386 b
3	3.55 a	34.1 ab	28.5 a	1.35 ab	0.994 a	1.95 ab

Table 10. Least squares means for effect of buffer-strip mowing height on concentration of pesticides and nutrients recovered in runoff water in August 1996.

Mowing	Pesticide Concentration			Nutrient Concentration		
Height	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0.5	6.37 a	85.5 a	41.7 a	1.02 ab	0.873 b	4.33 ab
1.5	8.52 a	116 a	52.6 a	1.44 a	1.20 a	6.43 a
1.5*	0.293 b	2.59 b	1.11 b	0.208 c	1.07 ab	2.30 b
3	9.32 a	103 a	48.5 a	0.878 b	1.16 ab	6.54 a

Table 11. Least squares means for effect of buffer-strip mowing height on mass of pesticides and nutrients recovered in runoff water in July 1996.

Mowing	Pesticide Mass			Nutrient Mass		
Height	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0.5	4280 a	51100 a	24600 a	1090 ab	491 a	2610 ab
1.5	4620 a	60300 a	29100 a	1410 ac	705 a	3240 a
1.5*	-253 b	-2300 b	-1930 b	691 b	676 a	124 b
3	2600 ab	22300 ab	19600 ab	966 bc	694 a	1240 ab

Table 12. Least squares means for effect of buffer-strip mowing height on mass of pesticides and nutrients recovered in runoff water in August 1996.

Mowing	Pesticide Mass			Nutrient Mass		
Height	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(in)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0.5	5710 a	76600 a	36400 a	763 abc	637 b	4220 a
1.5	6750 a	96300 a	42900 a	1210 ac	943 a	5160 a
1.5*	829 b	8140 b	4020 b	224 b	863 a	2430 b
3	7390 a	78400 a	37500 a	712 abc	915 a	5020 a

Means followed by different letters in the same column are significantly different ($P \leq 0.05$).
*Untreated Control.
** Source of applied N = urea.

Table 13. Time to start of runoff and total runoff water for buffer-strip length treatments in the July 1996 simulated rainfall event.

Buffer	Time to Start of Runoff		Runoff Volume	
Length	Mean	SD	Mean	SD
(ft)	(min)	(min)	(L)	(L)
0	16	6	223	45
4	17	8	230	57
8	21	8	339	114
16	19	5	358	147

Table 14. Time to start of runoff and total runoff water for buffer-strip length treatments in the August 1996 simulated rainfall event.

Buffer	Time to Start of Runoff		Runoff Volume	
Length	Mean	SD	Mean	SD
(ft)	(min)	(min)	(L)	(L)
0	17	6	278	50
4	16	7	350	34
8	20	6	423	79
16	20	8	455	48

Table 15 . Effect of buffer-strip length on concentration of pesticides and nutrients recovered in runoff water in July 1996.

Buffer	Pesticide Concentration			Nutrient Concentration		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0	7.50	130	60.5	1.78	0.762	4.50
4	3.50	66.3	28.0	1.89	0.767	2.79
8	1.00	39.8	13.5	1.42	0.945	1.52
16	4.00	49.3	26.3	2.14	1.16	1.39

Table 16 . Effect of buffer-strip length on concentration of pesticides and nutrients recovered in runoff water in August 1996.

Buffer	Pesticide Concentration			Nutrient Concentration		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0	13.8	183	79.5	1.89	1.30	10.3
4	9.50	126	54.8	160	1.18	7.02
8	7.75	103	44.3	1.39	1.35	6.20
16	7.00	93.8	41.5	1.44	1.56	5.57

Table 17. Effect of buffer-strip length on mass of pesticides and nutrients recovered in runoff water in July 1996.

Buffer	Pesticide Mass			Nutrient Mass		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0	1740	30300	14100	411	174	1050
4	857	16100	6810	445	182	673
8	495	15400	5520	518	311	551
16	1660	19800	10400	750	411	576

Table 18. Effect of buffer-strip length on mass of pesticides and nutrients recovered in runoff water in August 1996.

Buffer	Pesticide Mass			Nutrient Mass		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0	3830	51000	22100	526	361	2870
4	3290	43500	18900	544	410	2390
8	3250	43900	18900	605	573	2630
16	3160	42700	19000	660	714	2550

* Source of applied N = scu.

Table 19. Recovery of pesticides and nutrients in the July 1996 buffer-strip length study.

Buffer Length	Recovery in Runoff Water					
	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(ft)	(%*)	(%)	(%)	(%)	(%)	(%)
0	1.6	3.0	2.6	0.9	0.4	2.4
4	0.8	1.6	1.3	1.0	0.4	1.5
8	0.5	1.5	1.0	1.2	0.7	1.3
16	1.5	2.0	1.9	1.7	0.9	1.3

Table 20. Recovery of pesticides and nutrients in the August 1996 buffer-strip length study.

Buffer Length	Recovery in Runoff Water					
	Dicamba	2,4-D	Mecoprop	NH_4-N**	NO_3-N**	PO_4
(ft)	(%)	(%)	(%)	(%)	(%)	(%)
0	3.5	5.1	4.1	1.2	0.8	6.5
4	3.0	4.4	3.5	1.2	0.9	5.4
8	3.0	4.4	3.5	1.4	1.3	6.0
16	2.9	4.3	3.5	1.5	1.6	5.8

*Percentage of applied pesticide or nutrient recovered in runoff water.
** Source of applied N = scu.

Table 21. Least squares means for effect of buffer-strip length on concentration of pesticides and nutrients recovered in runoff water in July 1996.

Buffer	Pesticide Concentration			Nutrient Concentration		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0	7.88 a	135 a	61.7 a	1620 a	744 c	4.51 a
4	3.67 ab	68.2 b	28.5 b	1820 a	759 c	2.80 ab
8	0.530 b	34.3 b	12 b	1610 a	967 b	1.50 b
16	3.91 ab	48.3 b	26.0 b	2180 a	1160 a	1.39 b

Table 22. Least squares means for effect of buffer-strip length on concentration of pesticides and nutrients recovered in runoff water in August 1996.

Buffer	Pesticide Concentration			Nutrient Concentration		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug L^{-1})	(ug L^{-1})	(ug L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
0	13.6 a	182 a	79.3 a	1.80 a	1.29 b	10.1 a
4	9.32 b	124 b	54.5 b	1.50 a	1.17 b	6.87 b
8	7.94 b	105 b	44.5 b	1.48 a	1.36 ab	6.36 b
16	7.15 b	95.0 b	41.7 b	1.52 a	1.57 a	5.70 b

Table 23. Least squares means for effect of buffer-strip length on mass of pesticides and nutrients recovered in runoff water in July 1996.

Buffer	Pesticide Mass			Nutrient Mass		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0	2470 a	39500 a	18000 a	573 a	241 b	1360 a
4	1500 ab	24200 b	10200 bd	587 a	241 b	940 a
8	-85.4 c	8140 c	2420 c	390 a	258 b	310 b
16	866 bc	9860 c	6130 cd	575 a	338 a	247 b

Table 24. Least squares means for effect of buffer-strip length on mass of pesticides and nutrients recovered in runoff water in August 1996.

Buffer	Pesticide Mass			Nutrient Mass		
Length	Dicamba	2,4-D	Mecoprop	NH_4-N*	NO_3-N*	PO_4
(ft)	(ug)	(ug)	(ug)	(mg)	(mg)	(mg)
0	4340 a	62400 a	27500 a	697 a	496 ac	3390 a
4	3420 ac	46500 ac	20300 ac	589 a	446 c	2530 a
8	3010 bc	38600 bc	16400 bc	525 a	510 ab	2390 a
16	2750 c	33600 c	14700 c	524 a	606 a	2140 a

Means followed by different letters in the same column are significantly different ($P \leq 0.05$).

* Source of applied N = scu.

Appendix One

AMERICAN SOCIETY OF AGRONOMY
CROP SCIENCE SOCIETY OF AMERICA
SOIL SCIENCE SOCIETY OF AMERICA
677 South Segoe Road • Madison WI • 53711 • (608) 273-8080 • FAX (608) 273-2021

For reply, please address:
Dr. Warren A. Dick, JEQ Editor
School of Natural Resources, The Ohio State University
1680 Madison Avenue, Wooster, OH 44691-4096
Phone: (216) 263-3659; Fax: (216) 263-3658
E-mail: dick.5@osu.edu

"Influence of Buffer-Strip Length, Height, and Aerification on Pesticide and Nutrient Runoff from Bermudagrass Turf"

Paper No. Q- 96-310

Received 9/16/96

Dear Author:

The manuscript with the above title was received in our office on the date shown and given the above registration number. Please use this number as a reference on *all correspondence* regarding this paper.

The paper will be referred to an associate editor of the *Journal of Environmental Quality* for two or more reviews. If any revision of the paper is required, this information will be sent to you by either the associate editor or me. If the paper is approved for publication, you will be so advised. These steps may require as long as three months. If you do not receive word in that time or if we can be of assistance to you regarding this paper, please write to us.

With this letter I am sending you a Permission to Print and Reprint Form. JEQ is copyrighted as a collective work, and needs your permission to include your article. Individual articles are not copyrighted, as explained on the form. The form has two check items, one for U.S. government authors and another for nongovernment authors. Please check one of these items. **Return the form to ASA headquarters, at the address shown at the top left hand corner of this letter.**

If the paper is approved for publication, a charge will be made for printing. The current page charge to the author is $45 each for the first through fourth published page. Production charges are also levied against the author for each page over four pages at $90 per page. If you foresee any difficulty in paying the page and production charges, please inform us immediately before the paper is sent through the review process. If the paper is accepted for publication, an estimate of charges will be made and an order form for reprints will be sent to you at the time galleys are mailed. An invoice will be sent after publication.

Thank you for submitting your paper to the *Journal of Environmental Quality*.

Sincerely,

Warren A. Dick

Dr. W.A. Dick, JEQ Editor

November 1995

INFLUENCE OF BUFFER-STRIP LENGTH, HEIGHT, AND AERIFICATION ON PESTICIDE AND NUTRIENT RUNOFF FROM BERMUDAGRASS TURF

J.T. Cole, J.H. Baird,* N.T. Basta, R.L. Huhnke, D.E. Storm, G.V. Johnson, M.E. Payton, M.D. Smolen, D.L. Martin, and J.C. Cole

J.T. Cole, J.H. Baird, D.L. Martin, and J.C. Cole, Dep. of Hort. and Landscape Arch.; N.T. Basta and G.V. Johnson, Dep. of Agronomy; R.L Huhnke, D.E. Storm, and M.D. Smolen, Dep. of Biosystems and Agric. Eng.; M.E. Payton, Dep. of Statistics, Oklahoma State Univ., Stillwater, OK 74078-0511. Contribution of the Oklahoma Agric. Exp. Stn., Project 2264. Approved for publication by the Director, Oklahoma Agric. Exp. Stn. Received __________ 1996. *Corresponding author (jhbaird@okway.okstate.edu).

ABSTRACT

Public concern over pesticide and nutrient use and runoff from turf has increased. This study evaluated combinations of buffer-strip length (0, 2.4, and 4.9 m), mowing height (1.3 and 3.8 cm), and aerification to reduce pesticide and nutrient runoff from bermudagrass (*Cynodon dactylon* L. Pers.) turf on a Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls) on a 6% slope. Urea, sulfur-coated urea (SCU), triple superphosphate, chlorpyrifos [o,o-diethyl o-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] (granular and wettable powder), and the dimethylamine salts of 2,4-D (2,4-dichlorophenoxyacetic acid), mecoprop [2-(2-methyl-4-chlorophenoxy) propionic acid], and dicamba (3,6-dichloro-o-anisic acid) were applied at recommended rates on 8.8-m^2 plots (1.8-m width by 9.8-m length) located upslope of buffer-strips (0, 4.3, and 8.8-m^2). A portable rainfall simulator was used to apply precipitation rates of 51 or 64 mm h^{-1} for 75 to 140 min within 24 h after chemical application. In July 1995, soil moisture prior to simulated rainfall was low and pesticide and nutrient loss to surface runoff was less than 3% and 2%, respectively. Highest concentrations of pesticides and nutrients in runoff water were 314 $\mu g\ L^{-1}$ (2,4-D) and 9.57 mg L^{-1} (PO_4-P), respectively, from the treatment containing no buffer. In August, 165 mm of natural rainfall fell within 7 d of simulated rainfall and pesticide and nutrient loss to surface runoff was as great as 15% and 10%, respectively. Highest concentrations of pesticides and nutrients in runoff water were 174 $\mu g\ L^{-1}$ (2,4-D) and 8.14 mg L^{-1} (PO_4-P), respectively, from treatments containing no buffer. Reduced losses in surface runoff occurred from the wettable powder formulation of chlorpyrifos and the SCU form of nitrogen. Overall, buffer-

strips were effective in reducing pesticide and nutrient runoff. In most instances, buffer-strip mowing height, length (2.4 vs. 4.9 m), and aerification did not significantly reduce pesticide and nutrient runoff. The use of buffer-strips and avoidance of pesticide and nutrient application when soil is saturated may reduce chemical loss in surface runoff from turf.

The potential for runoff of pesticides and nutrients from turf, especially on golf courses, into surface water is the subject of increasing environmental concern. Approximately one-third (20 ha) of the total area of a typical golf course is comprised of fairway (Watson et al., 1992). Water hazards such as a sea, lake, pond, river, stream, or ditch may border the edge of the fairway and thus have the potential to collect contaminants in surface runoff.

Runoff occurs when infiltration rate is overcome by precipitation rate. Several factors affect surface loss of pesticides and nutrients including: 1) time interval between application and precipitation event causing runoff; 2) amount and duration of precipitation event; 3) antecedent soil moisture; 4) slope; 5) amount and method of chemical application; 6) timing of chemical application in regard to plant uptake; 7) chemical properties; 8) rate of field degradation; 9) soil properties; and 10) vegetation type (Walker and Branham, 1992; Balogh and Anderson, 1992). Pesticides and nutrients are lost in runoff as dissolved, suspended, or sediment-bound particles, the latter contributing to the greatest chemical losses (Walker and Branham, 1992; Balogh and Anderson, 1992). Runoff losses due to sediment are insignificant to most turf areas and, accordingly, turf has been shown to significantly reduce chemicals in surface runoff compared to tilled soil (Gross et al., 1990, 1991; Moe et al. 1968). A 2-year study in Rhode Island on creeping bentgrass (*Agrostis palustris* Huds.) putting greens recorded only two natural precipitation events that produced surface runoff; one of these events occurred on frozen ground and the other involved wet soils which received 125 mm of precipitation within one week (Morton et al., 1988). Brown et al. (1977) evaluated seasonal losses of nitrogen in leachate and runoff from sand- and soil-based creeping bentgrass putting greens. Nitrate concentrations in runoff from soil-based greens exceeded 10 mg L^{-1} only once and all other samples were below 5 mg L^{-1}. Linde et al. (1995) found that creeping bentgrass turf maintained under golf course fairway conditions reduced surface runoff when compared to perennial ryegrass (*Lolium perenne* L.). Bermudagrass (*Cynodon dactylon* L. Pers.), the dominant turfgrass species used on golf course fairways and many other areas in the southern United States, has not been studied regarding surface runoff.

Nitrogen and phosphorus are important and commonly-applied macronutrients required by the turfgrass plant for establishment, growth, and color. From an environmental standpoint, excessive losses of these nutrients into water features can result in eutrophication. Aquatic problems associated with increased algal growth can result from total nitrogen and phosphorus concentrations as low as 1 mg L^{-1} and 25 $\mu g\ L^{-1}$, respectively (Walker and Branham, 1992; Koehler et al., 1982). Nitrogen and phosphorus in surface runoff from turf is typically recovered in soluble forms as nitrate, ammonium, and phosphate, respectively (Walker and Branham, 1992). Morton et al. (1988) studied the influence of overwatering and fertilization on nitrogen losses in runoff from Kentucky bluegrass (*Poa pratensis* L.) turf. Mean concentrations of inorganic nitrogen in runoff water ranged from 0.36 mg L^{-1} on overwatered, unfertilized turf to 4.02 mg L^{-1} on overwatered, fertilized turf. Gross et al. (1990) found that runoff losses of nitrogen were significantly higher from fertilized tall fescue (*Festuca* arundinacea Schreb.)/Kentucky bluegrass turf when compared to unfertilized turf. No significant treatment differences were found in regard to phosphorus runoff losses.

The herbicides 2,4-D (2,4-dichlorophenoxyacetic acid), mecoprop [2-(2-methyl-4-chlorophenoxy) propionic acid], and dicamba (3,6-dichloro-o-anisic acid) are commonly used alone or in combination on turf for selective control of many broadleaf weed species. Likewise, the insecticide chlorpyrifos [o,o-diethyl o-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] is commonly used for control of surface- and root-feeding insects. Pesticides with water solubilites of greater than 10 ppm are predominantly lost in the soluble form in surface runoff (Wauchope, 1978). The water solubilities of 2,4-D, mecoprop, dicamba, and chlorpyrifos are 300,000 to 790,000 ppm, 660,000 ppm, 4,500 ppm, and 2.0 to 4.8 ppm, respectively (Balogh and Anderson, 1992). The adsorption affinity of pesticides to soil can be expressed by the adsorption coefficient (K_{OC}). The K_{OC} values for 2,4-D, mecoprop, dicamba, and chlorpyrifos are 20, 20, 2, and 6,070 to 14,000, respectively (Balogh and Anderson, 1992). Larger K_{OC} values, like that of chlorpyrifos, reflect a stronger degree of adsortion to soil particles. Watschke and Mumma (1989) studied the leaching and runoff characteristics of several pesticides including 2,4-D, dicamba, and chlorpyrifos applied to turf. Total losses in runoff were negligible for chlorpyrifos and less than 2% for the herbicides. White et al. (1976) observed similar concentrations of 2,4-D lost in runoff from an agricultural watershed.

Vegetated waterways and no-till buffer-strips have been shown to reduce surface runoff of chemicals in agricultural settings (Asmussen et al., 1977; Felsot et al., 1990; Chaubey et al., 1994). Buffer-strips help reduce surface runoff by: 1) increasing potential for infiltration; 2) reducing surface flow velocity; 3) providing a physical filtering effect; and 4) diluting applied chemicals (Muscutt et al., 1993). Dillaha et al. (1989) observed reductions in surface loss of nitrogen and phosphorus from plots containing vegetative filter strips. The evidence from these and other studies suggests that vegetation provides an effective filter for reducing surface runoff. However, the influence of the buffer-strip length, mowing height, and aerification on reducing nutrient and pesticide losses in surface runoff from turf has not been studied.

While vegetation, including turf, may serve as an effective filter of chemicals, it is less effective when an unforeseen, heavy precipitation event closely follows the application of pesticides and fertilizer (Balogh and Anderson, 1992). The objective of this study was to evaluate the effects of buffer-strip length, mowing height, solid-tine aerification, and pesticide and fertilizer formulation on surface losses in runoff of 2,4-D, dicamba, mecoprop, chlorpyrifos, nitrogen, and phosphorus from simulated bermudagrass fairways following a heavy precipitation event. The pesticides and fertilizer were chosen for this study because of their widespread use by turf managers and potential for surface runoff based upon their physico-chemical properties.

MATERIALS AND METHODS

Site Preparation

This study was conducted in July and repeated in August 1995 on a 1.2-ha common bermudagrass sloped field located at the Oklahoma State University Agronomy Farm in Stillwater. The soil is a Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls). The turf was mowed at 1.3 cm three times per week and fertilized with nitrogen at 98 kg N ha^{-1} in August 1994 and 49 kg N ha^{-1} in May 1995 from urea (46N-0P-0K) to achieve golf course fairway turf conditions. Differential leveling techniques were used to define contour lines in order to determine suitable locations for 8 rainfall simulator setups, each containing four plots. Plot locations were staked out and then minor adjustments were made to insure that plots were parallel to the slope and that they contained no significant surface depressions. The average slope of the plots was 6% (±0.6%).

Rainfall Simulator

A portable rainfall simulator was used to apply controlled precipitation on an area consisting of four 1.8-m x 9.8-m plots. The rainfall simulator is based on the Nebraska rotating-boom design (Swanson, 1979), and is capable of wetting a 15.2-m diameter area. The nozzles, located on a rotating boom 2.7 m above the ground, spray continuously and move in a circular pattern. The rainfall simulator boom was rotated at approximately 7 revolutions per minute. Figure 1 shows the simulator location and plots for one setup. A central alley, 3-m wide, allowed room for the simulator placement between plots 2 and 3 with at least a 1.5 m boom overhang at all corners to ensure uniform rainfall coverage. The rainfall simulator was set parallel to the land surface with the boom held at a constant height above the ground. Plot pairs were separated by 0.3 m. The rainfall simulator was calibrated prior to the experiment; however, three rain gauges were installed in the center alley, 2.4, 4, and 5.5 m from the boom center to measure delivered rainfall.

Each rainfall simulation experiment required 14,500 to 21,600 l of water, depending upon the rainfall intensity and length of the rainfall simulation event. A 19,000-l tanker was used for storage of water supplied by a City of Stillwater fire hydrant. A 5.2-kW gasoline engine and pump, located at the tanker, pumped the water through a 5-cm high-pressure vinyl hose to the simulator. The pump provided a mast-head pressure set at 207 kPa.

Plot Construction

Plot borders were made using lengths of flexible 3.8-cm i.d. plastic discharge hose (Amazon Hose and Rubber Co., Chicago, IL) filled with masonry sand. Plot borders were laid onto the turf and a sand:bentonite clay (5:1 v/v) mix was used to seal the outside edge of the hose to eliminate runoff from flowing underneath the borders.

A 6-mm deep lip and a 150-mm deep trench was dug down slope of the plots to install the endplates and collection troughs. An endplate consisting of 1.9-m long angle Aluminum (75-mm x 75-mm x 3-mm) with a sheet of 22 gage galvanized steel riveted onto one of the legs was placed at the lower end of each plot (Figure 2). The Al angle served as a shelf, while the galvanized sheet channeled the runoff into a collection trough. Melted paraffin was poured along the inside edge of the endplate to form a seal between the endplate and soil to insure that runoff would not flow underneath. The collection trough for each plot consisted of an approximately 2-m section of 150-mm diameter PVC pipe split length-wise. Blocks were placed under the troughs to provide a positive slope toward the collection pits. A sheet metal frame covered and protected the collection trough from rainwater and other contaminants. The collection pits were approximately 1-m wide by 1-m deep, and were reinforced with sheet metal and iron frame. Excess runoff accumulating in the three pits was emptied by sump pumps.

Plot Preparation

Prior to the rainfall simulation event, plots received uniform irrigation only when the turf was under moisture stress and for durations that did not produce measurable runoff. Plots were mowed with a reel mower and clippings were left in place. Each plot area (1.8 m x 4.9 m) receiving pesticide and fertilizer was mowed at 1.3 cm to represent a golf course fairway. The buffer area was considered to represent a golf course rough or the area between the treated area (fairway) and runoff collection point (surface water feature). The buffer was mowed at 1.3 cm to represent no rough or 3.8 cm to represent a standard mowing height for bermudagrass rough in Oklahoma. A deep, solid-tine aerator (Aer-Way, Norwich, ON, Canada) was used to punch approximately one hole (19-mm diameter x 165-mm deep) per 51 mm^2. The solid-tine aerification treatment was performed on the buffer area only.

July Simulated Rainfall Event

Treatments are shown in Table 1. The following fertilizers and pesticides were applied to the treated area: nitrogen at 49 kg N ha^{-1} from urea (46N-0P-0K);

phosphorus at 49 kg P ha^{-1} from triple superphosphate (0N-20P-0K); chlorpyrifos 0.5 G (Howard Johnson's Ent., Inc., Milwaukee, WI) at 2.2 kg ai ha^{-1}; and 2,4-D at 1.1 kg ae ha^{-1}, mecoprop at 0.6 kg ae ha^{-1}, and dicamba at 0.1 kg ae ha^{-1} formulated as dimethylamine salts in Trimec® Classic (PBI-Gordon, Kansas City, KS). Fertilizer and insecticide were applied and irrigated with 5 mm of water using the rainfall simulator calibrated to deliver 51 mm h^{-1} for 6 min. The herbicides were subsequently applied after the wetted turf had dried using a CO_2-powered ground sprayer set to deliver 187 l ha^{-1} of water. An additional treatment (H) received no pesticides or nutrients. Simulated rainfall was applied within 24 h of application of pesticides and nutrients. Rainfall intensity was set at 51 mm h^{-1}.

August Simulated Rainfall Event

Treatments are shown in Table 5. Treatments A-G were repeated in August. Treatment H, an untreated control in July, was replaced by treatment I in August. Treatment I, containing no buffer-strip, substituted identical rates of the 50 WP formulation (DowElanco, Indianapolis, IN) for the granular formulation of chlorpyrifos and a sulfur-coated urea (39-0-0) (Greenskote Trikote Poly SCU, Pursell Indust., Sylacauga, AL) for the urea formulation of nitrogen fertilizer. Fertilizer and insecticide were applied and irrigated as described in the July simulated rainfall event. Simulated rainfall was applied within 24 h of application of pesticides and nutrients. Rainfall intensity was set at 64 mm h^{-1}.

Experimental Design

The experimental design was an unbalanced, randomized incomplete block. An unbalanced design was used because adjacent land was unsuitable to construct additional simulator set-ups to test the number of treatments in this study. Nevertheless, the design insured that important treatment comparisons (shown in Tables 1 and 4) were contained in the same simulator setup (block) at least twice. Each treatment was replicated 4 times. Data were subjected to analysis of covariance (ANCOVA). The time to the start of runoff and total runoff volume for each plot were used as covariates in the analyses of concentration and mass, respectively, in order to account for differences in runoff that were due to differences in antecedent soil moisture or natural variation in soil properties. Furthermore, soil moisture content of each simulator region was determined by gravimetric analysis prior to rainfall simulation.

Sampling

Two simulated rainfall events were conducted per day. Start of runoff was recorded when a continuous trickle of water was first observed at the collection pit. Samples were collected at preset times after the start of runoff for individual plots using a nominal sampling schedule. Samples were taken more frequently during the rising portion of the hydrograph. Most plots were sampled 10 times during the simulated rainfall period. In addition to sample collection for analysis, runoff water samples of 0.45 l, 1.0 l, or 5.0 l were collected depending upon the flow rate of runoff. The time required to fill a calibrated sample container was used to calculate the runoff rate. Time was measured to within 0.1 s with a hand-held stopwatch. The accuracy of the runoff flow rate was estimated to be within 3%. Discharge measurements, sample times, weather, precipitation, and plot conditions were recorded for each simulated rainfall event. Volume-weighted composites were prepared for runoff samples from each plot. In addition, a sample of the simulated rain water was taken directly from a simulator nozzle during each run.

Pesticide Analysis

The following procedures were adopted from DiCorcia and Marchetti (1992). All organic solvents were high performance liquid chromatography (HPLC) grade and deionized water was ≥15 MΩ. Runoff samples were vacuum filtered through 0.45-μ nylon membrane filters and refrigerated at 4 °C until analyzed (<48 h). Filtered samples (100 ml) were passed through Carbopack B solid phase extraction (SPE) columns (Supelco, Inc.). Air was drawn through the column for one min to dry the SPE column. Acidic (2,4-D, dicamba, mecoprop) and base/neutral (chlorpyrifos) pesticides were adsorbed from the runoff water by the SPE column. Bases followed by acids were eluted from the SPE column in sequence.

Chlorpyrifos was eluted with 1- x 2-ml then 2- x 1-ml solutions of 80:20 (v/v) methylene chloride (MeCl): methanol (MeOH). Column eluates were combined in a 4-ml HPLC vial and placed in a water bath at 35 °C. Chlorpyrifos was concentrated by evaporation of the eluate to 1 ml under a gentle stream of ultra-high purity He gas. Eluate was reconstituted to 2 ml with 50:50 MeOH:H_2O. Chlorpyrifos was determined by HPLC analysis as described below.

After chlorpyrifos was eluted, acidic pesticides were eluted from the SPE column by 3 x 1 ml of acidified 80:20 (v/v) MeCl:MeOH (acidified with 0.17% trifluoroacetic acid, TFA). Column eluates were combined in a 4-ml HPLC vial and placed in a water bath at 35 °C under a stream of He until dry. The pesticide residue was reconstituted with 2.0 ml of 50:50 (v/v) MeOH:H_2O. Acidic pesticides (2,4-D, dicamba, and mecoprop) were determined by HPLC analysis.

Pesticides were determined using a Model 500 HPLC (Dionex, Sunnyvale, CA). Components included a 50-µl injector, LC-18 HPLC column (Varian, Walnut Creek, CA), and UV-VIS detector (Dionex). Chlorpyrifos and acidic pesticides were analyzed by different HPLC methods.

Chlorpyrifos Analysis

The mobile phase flow rate was 1.5 ml min^{-1}. The mobile phase was 15% 1 mM sodium phosphate buffer (pH 6.7) and 85% acetonitrile (ACN). Chlorpyrifos had a retention time of 3.2 min and was measured at 230 nm. The detection limit was 0.01 µg L^{-1} chlorpyrifos in runoff water.

2,4-D, Dicamba, and Mecoprop Analysis

The mobile phase flow rate was 1.5 ml min^{-1}. The acidic pesticides were separated using premixed MeOH:ACN (82:18, v/v) as an organic eluent and water acidified with TFA (0.17% TFA, v/v). The initial mobile phase was 50% organic eluent and 50% acidified water, which was linearly increased to 62% organic eluent after 15 minutes. Acidic pesticides were measured at 220 nm. Retention times of 5.7, 8.0, and 11.2 min were observed for dicamba, 2,4-D, and mecoprop, respectively. The detection limit was 0.01 µg L^{-1} of each acidic pesticide in runoff water samples.

Nutrient Analysis

Phosphate, ammonium, and nitrate were measured in filtered runoff samples. Phosphorus was determined by the phosphomolybdate colorimetric procedure employed by Murphy and Riley (1962). NH_4-N and NO_3-N were determined by colorimetric methods using automated flow injection analysis (Lachat, 1989, 1990). The detection limit was 0.01 mg L^{-1} of each nutrient in runoff water samples.

RESULTS AND DISCUSSION

July Simulated Rainfall Event

No natural precipitation occurred within 12 d prior to or during the July rainfall simulation events. Soil moisture content of each rainfall simulation area ranged from 15 to 19% by weight (data not shown). Rainfall simulation events lasted between 75 and 140 min; rainfall events longer than 75 minutes were necessary in order to collect enough runoff samples for analysis given the dry soil moisture conditions. A range from 0.5 to 16% of the simulated rainfall water left the plots as runoff during the events (data not shown). Time to start of runoff and total runoff volume of each treatment ranged from 21 to 76 min and 52 to 161 L, respectively (Table 1). Variation in time to start of runoff and total runoff volume were most likely caused by differences in antecedent soil moisture or natural variation in soil properties among the plot areas. For example, greater volumes of runoff water were not always collected from treatments containing the longer buffer-strips even though these treatments contained greater surface area to receive and potentially lose simulated rainfall. Buffer-strip treatments mowed at 3.8 cm reduced the total volume of surface runoff water compared to the 1.3-cm buffers, except when the buffer-strips were aerified. There were no significant differences ($P \geq 0.05$) due to buffer mowing height or aerification, except for concentration of chlorpyrifos in runoff, which was increased in one comparison by the 1.3-cm mowing height and in another comparison by aerification (Tables 2 and 3). Inconsistencies in numerical trends among comparisons of mowing height and aerification in terms of pesticide and nutrient concentration could be explained by dilution effects caused by differences in treatment runoff volume (Tables 1 and 2). For example, runoff losses of most of the pesticides and nutrients were increased by the 4.9-m buffer-strip mowed at 3.8 cm but decreased by the 2.4-m buffer-strip mowed at the same height (Table 2). In terms of pesticide and nutrient mass, numerical trends indicated that the 3.8-cm mowing height helped reduce runoff losses, compared with the 1.3-cm height, except when aerified. Also, aerification helped reduce runoff losses except when the buffer was mowed at the 3.8-cm mowing height. These results are in agreement with the total runoff volume data shown in Table 1. It is possible that the aerification process created channels in the taller turf canopy, thus creating a less tortuous pathway for movement of the chemicals in surface runoff. Treatments containing buffer-strips were effective in reducing losses of all pesticides, NH_4-N, and PO_4 in runoff water compared to no buffer-strip (Tables 2 and 3). There were no significant differences ($P \geq 0.05$) in runoff losses in comparisons between the 2.4- and 4.9-m buffer-strips; however, numerical trends showed greater runoff losses from the shorter buffer-strip. No significant treatment differences ($P \geq 0.05$) were observed for NO_3-N most likely because very little of the urea was nitrified to NO_3-N within 24 h of application; therefore, most of the NO_3-N recovered in runoff probably pre-existed in soil. Moe et al. (1968) noted similar findings when comparing nitrogen losses from urea and ammonium nitrate in runoff water. Chaubey et al. (1994) found that tall fescue buffer-strips did not significantly reduce NO_3-N in runoff losses from a source area treated with swine manure; the buffer-strips did significantly reduce runoff losses of NH_3-N and PO_4. Percent recovery of pesticides and nutrients was less than 3.1% and 1.9%, respectively, based upon the total mass applied (Table 4). In many instances, nutrient recovery in runoff was greater from unfertilized plots compared to fertilized plots.

August Simulated Rainfall Event

In contrast to July, 165 mm of natural precipitation was measured within 7 d of rainfall simulation events in August. No natural precipitation occurred during the simulated rainfall events. Based on the inordinately long times to start of runoff and low total runoff volumes in the July event, the decision was made to increase rainfall intensity to 64 mm h^{-1} in the August event. Soil moisture content of each rainfall simulation area ranged from 25 to 30% by weight (data not shown). All rainfall simulation events lasted 75 min. A range from 31 to 81% of the simulated rainfall water left the plots as runoff during the events (data not shown). Time to start of runoff and total runoff volume of each treatment ranged from 13 to 22 min and 498 to 819 L, respectively (Table 5). Runoff occurred as much as six times faster and total runoff volume was as much as 16 times greater in August compared to July. Similar to the July simulated rainfall events, mean runoff volumes were lower from the treatments containing the 3.8-cm buffer heights compared to the 1.3-cm height. Higher soil moisture in August resulted in greater runoff of pesticides and nutrients compared to July (Tables 6, 7 and 8). Unlike numerical trends observed in the July simulated rainfall events, significant differences ($P \leq 0.05$) in runoff concentrations and mass for comparisons of buffer-strip mowing height indicated reduced runoff losses from buffer-strips mowed at 1.3-cm compared to 3.8 cm (Tables 6 and 7). Linde et al. (1995) attributed reduced surface water runoff from creeping bentgrass to its stoloniferous growth habit and greater turf density when compared to perennial ryegrass. It is possible that reduced runoff losses from bermudagrass turf mowed at 1.3 cm compared to 3.8 cm were related to increased turf density achieved by a lower height of cut. On the contrary, the taller height of cut occasionally reduced chemical losses in runoff most likely by intercepting the flow of water of the plots. As such, results comparing buffer-strip mowing height effects on runoff were inconclusive and require further experimentation. Fewer significant differences were observed for the effect of buffer-strip length on pesticide and nutrient runoff in August compared to July. Thus it appeared that the effectiveness of the buffer-strip treatments was lessened by antecedent soil moisture conditions and the increased volume of surface runoff. The buffer-strip treatments did cause significant reduction of chlorpyrifos in runoff water compared to the treatments containing no buffer-strip. Chlorpyrifos is a relatively water insoluble pesticide; therefore, it is likely that the buffer-strip treatments would contribute to reduced chemical loss even when the potential for runoff is great. No significant differences were observed for comparisons involving aerification; however, numerical trends indicated that the holes created by aerification contributed more positively, perhaps through greater infiltration, to reduced pesticide and nutrient runoff under wet conditions in August compared to drier conditions in July. Reduced pesticide and nutrient runoff occurred from the wettable powder formulation of chlorpyrifos compared to the granular formulation, and from the sulfur-coated urea form of nitrogen compared to urea. In a review of pesticide losses due to runoff, Wauchope (1978) noted several studies where the wettable powder formulations of herbicides showed the greatest long-term losses in runoff. Most of the studies reviewed were on agricultural soils and compared wettable powders to other sprayable formulations not including granulars. Although wettable powder formulations may be subject to runoff, granular formulations would appear to be subject to the greatest runoff losses, especially when a heavy precipitation event closely follows application. Reduced runoff losses of chlorpyrifos from the wettable powder formulation was most likely due to its ability to become bound and incorporated into turf more rapidly than the granular formulation. The reduction in the percent of nitrogen recovered by the SCU formulation can be explained by the slow breakdown of the coating in water thus reducing soluble nitrogen sources from entering the runoff water. Dunigan et al. (1976) and Brown et al. (1982) reported reduced runoff losses of nitrogen from slow compared to quick release nitrogen fertilizers. Percent recovery of pesticides and nutrients was as great as 15% and 11%, respectively (Table 8). Asmussen et al. (1977) reported 2.5% and 10.3% runoff losses of 2,4-D under dry and wet soil moisture conditions, respectively. Similar effects of soil moisture on nutrient runoff were reported by Moe et al. (1967) and Morton et al. (1988).

Overall, these results suggest that turf is an effective filter to chemicals. Furthermore, use of turf buffer-strips can significantly reduce chemical losses in runoff. Buffer-strips help reduce surface runoff by: 1) increasing potential for infiltration; 2) reducing surface flow velocity; 3) providing a physical filtering effect; and 4) diluting applied chemicals (Muscutt et al., 1993). Chemical dilution was an important factor in this study since addition of a buffer increased the plot area receiving simulated rainfall. Buffer-strip mowing height and aerification did not significantly contribute to reduced runoff losses within the parameters of this study. Perhaps larger differences in mowing height, different aerification practices (e.g., hollow-tine), or application of these treatments on a larger scale watershed would cause a significant reduction in surface runoff of pesticides and nutrients.

The U. S. Environmental Protection Agency (EPA) has set Lifetime Health Advisory Levels in drinking water for dicamba, 2,4-D, mecoprop, chlorpyrifos, and nitrate in drinking water at 200 $\mu g\ L^{-1}$, 70 $\mu g\ L^{-1}$, 7 $\mu g\ L^{-1}$, 20 $\mu g\ L^{-1}$, and 10 $mg\ L^{-1}$, respectively (EPA, 1989). Although water features surrounding golf courses are not typically used for drinking, results from the July simulated rainfall event indicated that use of a buffer-strip reduced pesticide and nutrient concentrations in runoff to levels below EPA standards. Higher soil moisture conditions in August increased pesticide and nutrient concentrations in runoff, especially 2,4-D and mecoprop, to levels exceeding EPA standards. A more relevant indication of the potential for contamination of surface waters on golf courses is the effect on aquatic organisms. The lethal concentrations (LC_{50}) found to kill 50% of bluegill, a common freshwater fish, are >2.4 $\mu g\ L^{-1}$ for chlorpyrifos (Johnson and Finley, 1980), >8000 $\mu g\ L^{-1}$ for 2,4-D (Hughes and Davis, 1963), and >50,000 $\mu g\ L^{-1}$ for dicamba (Johnson and Finley, 1980). Most of the treatments containing buffer-strips were effective in reducing pesticide concentrations below these critical values. The concentration of nutrients in runoff from all treatments exceeded minimum levels that have been found to enhance eutrophication. However, results from the July simulated rainfall indicated that only a small amount of the nutrients recovered in runoff water, especially from treatments containing buffers, was from the applied fertilizer. The correlation between the physico-chemical properties of pesticides and nutrients and their relative runoff potential was substantiated by this investigation. Greater runoff losses occurred from the herbicides and urea fertilizer which have higher water solubilities compared to the insecticide chlorpyrifos and SCU fertilizer.

Based upon this investigation, the following management practices are recommended to reduce pesticide and nutrient runoff from turf: 1) establish a buffer-strip between surface water features and treated areas; 2) avoid application of pesticides and fertilizer when high soil moisture conditions exist; 3) develop pest and nutrient management programs that utilize pesticide and fertilizer formulations with low runoff potential. Our results suggest that use of slow release nitrogen fertilizers, wettable powder instead of granular formulations of pesticides, and pesticides with lower water solubilities will reduce runoff potential. Further research is needed to determine critical soil moisture levels, buffer-strip lengths, mowing heights, and associated factors that result in reduced pesticide and nutrient runoff from turf.

ACKNOWLEDGMENTS

This paper reports research supported by a grant from the U.S. Golf Assoc., Far Hills, NJ. The authors wish to thank Dr. William Raun, Associate Professor of Agronomy, for insightful suggestions, and Steve Wilcoxen, Superintendent of Karsten Creek Golf Club, for use of a deep-tine aerator.

REFERENCES

Asmussen, L.E., A.W. White, E.W. Hauser, and J.M. Sheridan. 1977. Reduction of 2,4-D load in surface runoff down a grassed waterway. J. Environ. Qual. 6(2):159-162.

Balogh, J.C. and J.L. Anderson. 1992. Environmental impacts of turfgrass pesticides. *In* Balogh, J.C. and W.J. Walker, (ed.). Golf Course Management and Construction: Environmental Issues. Lewis Publishers, Chelsea, MI, Chapter 3.

Brown, K.W., R.W. Duble, and J.C. Thomas. 1977. Influence of management and season on fate of N applied to golf greens. Agron. J. 69(4):667--671.

Brown, K.W., J.C. Thomas, and R.W. Duble. 1982. Nitrogen source effect on nitrate and ammonia leaching and runoff losses from greens. Agron. J. 74(6):947-950.

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, Jr., and D. J. Nichols. 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. Trans. ASAE 37(3):845-850.

Di Corcia, A. and M. Marchetti. 1992. Method development for monitoring pesticides in environmental waters: Liquid-solid extraction followed by liquid chromatography. Environ. Sci. Tech. 26:66-74.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Trans. ASAE 32(2):513-519.

Dunigan, E.P., R.A. Phelan, and C.L. Mondart, Jr. 1976. Surface runoff losses of fertilizer elements. J. Environ. Qual. 5(3):339-342.

Environmental Protection Agency. 1989. Health Advisory Summaries. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Felsot, A.S., J.K. Mitchell, and A.L. Kenimaer. 1990. Assessment of management practices for reducing pesticide runoff from sloping cropland in Illinois. J. Environ. Qual. 19(3):539-545.

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

Gross, C.M., J.S. Angle, R.L. Hill, R.L. and M.S. Welterlen. 1991. Runoff and sediment losses from tall fescue under simulated rainfall. J. Environ. Qual. 20(3):604-607.

Hughes, J.S. and J.T. Davis. 1963. Variations in toxicity to bluebill sunfish of phenoxy herbicides. Weeds 2(1):50-53.

Johnson, W.W. and M.T. Finley. 1980. Handbook of Acute Toxicity to Fish and Aquatic Invertebrates. Resour. Publ. 137. Fish Wildl. Serv., U.S. Dept. Int., Washington, D.C., 98 pp.

Koehler, F.A., F.J. Humenik, D.D. Johnson, J.M. Kreglow, S.A. Dressing, and R.P. Maas. 1982. Best Management Practices for Agricultural Nonpoint Source Control. II. Commercial fertilizer. USDA Coop. Agree. 12-05-300-472. EPA Interagency Agree. AD-12-F-0-037-0. North Carolina Agric. Ext. Serv., Raleigh, NC, 55 pp.

Lachat Instruments. 1989. Quickchem method 12-107-04-1-B. Lachat Instr., Milwaukee, WI.

Lachat Instruments. 1990. Quickchem method 12-107-06-1-B. Lachat Instr., Milwaukee, WI.

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

Moe, P.G., J.V. Mannering, and C.B. Johnson. 1967. Loss of fertilizer nitrogen in surface runoff water. Soil Sci. 104(6):389-394.

Moe, P.G., J.V. Mannering, and C.B. Johnson. 1968. A comparison of nitrogen losses from urea and ammonium nitrate in surface runoff water. Soil Sci. 105(6):428-433.

Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. J. Environ. Qual. 17(1):124-130.

Muscutt, A.D., G.L. Harris, S.W. Bailey, and D.B. Davies. 1993. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agric. Ecosytems Environ. 45:59-77.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27:31-36.

Swanson, N.P. 1979. Field plot rainfall simulation (rotating-boom rainfall simulator) in Lincoln, Nebraska. Proceedings of the Rainfall Simulator Workshop, Tucson, AZ, 166-169. USDA-SEA Agricultural Reviews and Manuals ARM-W-10/July.

Watschke, T.L. and R.O. Mumma. 1989. The Effect of Nutrients and Pesticides Applied to Turf on the Quality of Runoff and Percolating Water. A Final Report to the U.S. Dept. Int., U.S. Geol. Sur. ER 8904. Env. Res. Inst., Penn State University, College Park, PA, 64 pp.

Watson, J.R., H.E. Kaerwer, and D.P. Martin. 1992. The turfgrass industry. *In* D.V. Waddington, R.N. Carrow, and R.C. Shearman (ed.) Turfgrass, ASA Monograph No. 32, Madison, WI, pp. 29-88.

Walker, W.J. and B. Branham. 1992. Environmental impacts of turfgrass fertilization. *In* Balogh, J.C. and W.J. Walker, (ed.). Golf Course Management and Construction: Environmental Issues. Lewis Publishers, Chelsea, MI, Chapter 3.

Wauchope, R.D. 1978. The pesticide content of surface water draining from agricultural fields - A review. J. Environ. Qual. 7(4):459-472.

White, A.W., L.E. Asmussen, E.W. Hauser, and J.W. Turnbull. 1976. Loss of 2,4-D in runoff from plots receiving simulated rainfall and from a small agricultural watershed. J. Environ. Qual. 5:487-490.

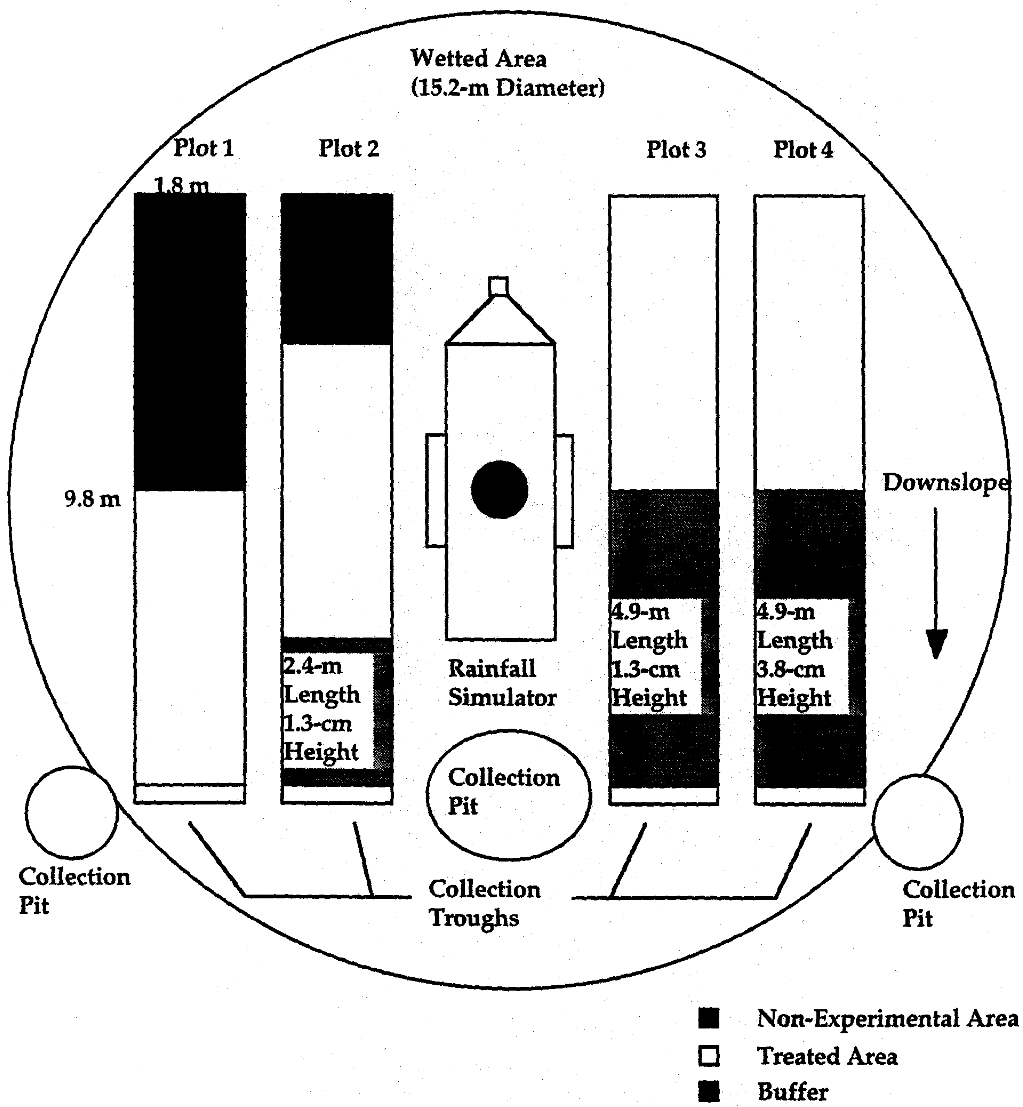
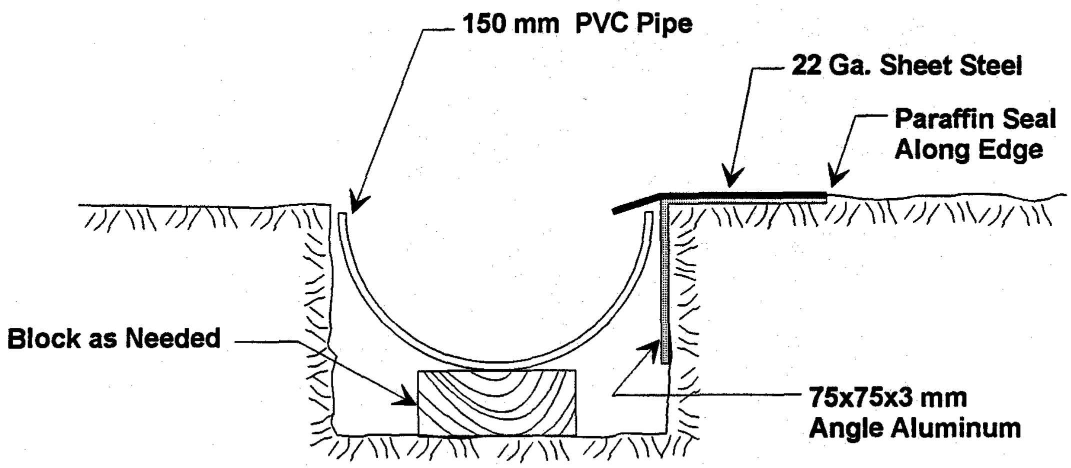


Fig. 1. Rainfall simulator and example of plot layout. Ten booms with staggered nozzles not shown.



Endplate and Collection Trough

Figure 2. Cross-section view of plot area showing position of endplate and collection trough.

Table 1. Time to start of runoff and total volume of runoff water for treatments in the July 1995 simulated rainfall event.

Treatment	Buffer Length	Buffer Height	Aerification	Time to start of Runoff Mean	Time to start of Runoff SD	Runoff Volumne Mean	Runoff Volumne SD
	(m)	(cm)		(min)	(min)	(L)	(L)
A	4.9	1.3	No	76.0	46.8	109.0	105.0
B	4.9	3.8	No	62.2	51.5	52.3	58.8
C†	0	-	-	55.8	56.6	64.4	62.8
D	2.4	1.3	No	21.1	27.9	161.0	104.0
E	2.4	3.8	No	56.1	42.4	74.1	121.0
F	4.9	1.3	Yes	50.8	36.7	53.6	32.0
G	4.9	3.8	Yes	55.5	38.9	126.0	153.0
H‡	0	-	-	30.8	49.2	129.0	118.0

†Treatment C = no buffer; pesticides and nutrients applied.

‡Treatment H = no buffer; no pesticides and nutrients applied.

Table 2. Concentration and tests of significance for comparisons of the effect of management practices on concentration of pesticides and nutrients recovered in runoff water in the July 1995 simulated rainfall event.

				Pesticide Concentration				Nutrient Concentration		
Treatment	Buffer Length	Buffer Height	Aerification	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
	(m)	(cm)		($\mu g\ L^{-1}$)				($mg\ L^{-1}$)		
A	4.9	1.3	No	1.00	14.40	6.30	5.73	3.47	3.44	1.02
B	4.9	3.8	No	4.79	26.90	15.50	4.64	5.33	3.99	1.35
C†	0	-	-	16.50	314.00	164.00	34.80	7.40	2.49	9.57
D	2.4	1.3	No	3.69	76.90	44.90	4.49	4.94	2.74	2.36
E	2.4	3.8	No	1.34	31.00	15.30	0.00	4.85	3.93	1.94
F	4.9	1.3	Yes	0.00	15.80	14.40	20.50	2.82	3.05	0.783
G	4.9	3.8	Yes	0.00	13.20	6.38	7.25	4.50	3.45	1.25
H‡	0	-	-	0.00	0.00	0.00	0.00	2.41	2.56	0.422
COMPARISONS										
Buffer Mowing Height (1.3 vs. 3.8 cm)				NS	NS	NS	NS	NS	NS	NS
A vs. B				NS	NS	NS	NS	NS	NS	NS
D vs. E				NS	NS	NS	NS	NS	NS	NS
F vs. G				NS	NS	NS	*§	NS	NS	NS
Buffer Length (2.4 vs. 4.9 m)				NS	NS	NS	NS	NS	NS	NS
A vs. D				NS	NS	NS	NS	NS	NS	NS
B vs. E				NS	NS	NS	NS	NS	NS	NS
Buffer Length (0 vs. 2.4 m)										
C vs. D				**	**	**	**	*	NS	**
C vs. E				**	**	**	**	NS	NS	**
Buffer Length (0 vs. 4.9 m)										
C vs. A				**	**	**	**	**	NS	**
C vs. B				**	**	**	**	*	NS	**
C vs. F				**	**	**	NS	**	NS	**
Aerification (yes vs. no)				NS	NS	NS	NS	NS	NS	NS
A vs. F				NS	NS	NS	*	NS	NS	NS
B vs. G				NS	NS	NS	NS	NS	NS	NS
Control										
H vs. C				**	**	**	**	**	NS	**

†Treatment C = no buffer; pesticides and nutrients applied.
‡Treatment H = no buffer; no pesticides and nutrients applied.
§*,** Significant at alpha levels 0.05 and 0.01, respectively. NS=Not Significant.

Table 3. Mass and tests of significance for comparisons of the effects of management practices on mass of pesticides and nutrients recovered in runoff water in the July 1995 simulated rainfall event.

Treatment	Buffer Length	Buffer Height	Aerification	Pesticide Mass Dicamba	2,4-D	Mecoprop	Chlorpyrifos	Nutrient Mass NH_4-N	NO_3-N	PO_4
	(m)	(cm)		(μg)				(mg)		
A	4.9	1.3	No	3	2730	1380	963	480	381	136
B	4.9	3.8	No	156	1860	1050	27	264	170	71
C[†]	0	-	-	1580	30800	16200	2780	642	147	911
D	2.4	1.3	No	876	17200	10000	984	813	363	471
E	2.4	3.8	No	341	6010	3050	0	410	186	276
F	4.9	1.3	Yes	0	768	874	1070	125	143	37
G	4.9	3.8	Yes	0	3510	1730	877	672	462	246
H[‡]	0	-	-	0	0	0	0	401	340	51

COMPARISONS	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
Buffer Mowing Height (1.3 vs. 3.8 cm)	NS	NS	NS	NS	NS	*[§]	NS
A vs. B	NS	NS	NS	NS	NS	NS	NS
D vs. E	NS	NS	NS	NS	NS	NS	NS
F vs. G	NS	NS	NS	NS	NS	NS	NS
Buffer Length (2.4 vs. 4.9 m)	NS	NS	NS	NS	NS	*	NS
A vs. D	NS	NS	NS	NS	NS	*	NS
B vs. E	NS	NS	NS	NS	NS	NS	NS
Buffer Length (0 vs. 2.4 m)							
C vs. D	NS	NS	NS	NS	NS	NS	NS
C vs. E	*	*	*	*	NS	NS	*
Buffer Length (0 vs. 4.9 m)							
C vs. A	**	**	**	NS	NS	NS	**
C vs. B	**	**	**	**	NS	NS	**
C vs. F	NS	*	NS	*	*	NS	*
Aerification (yes vs. no)	NS	NS	NS	NS	NS	NS	NS
A vs. F	NS	NS	NS	NS	NS	NS	NS
B vs. G	NS	NS	NS	NS	NS	NS	NS
Control							
H vs. C	**	**	**	**	*	NS	**

[†]Treatment C = no buffer; pesticides and nutrients applied.
[‡]Treatment H = no buffer; no pesticides and nutrients applied.
[§]*,** Significant at alpha levels 0.05 and 0.01, respectively. NS=Not Significant.

Table 4. Percent recovery of pesticides and nutrients in runoff water in the July simulated rainfall event.

				Recovery in Runoff Water						
				Pesticides				Nutrients		
Treatment	Buffer Length	Buffer Height	Aerification	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
	(m)	(cm)		(%)[†]				(%)		
A	4.9	1.3	No	0.003	0.27	0.26	0.05	0.18	0.09	0.19
B	4.9	3.8	No	0.14	0.19	0.19	0.001	-0.31	-0.44	0.05
C[‡]	0	-	-	1.40	3.10	3.00	0.14	0.55	-0.44	1.90
D	2.4	1.3	No	0.80	1.70	1.80	0.05	0.94	0.05	0.96
E	2.4	3.8	No	0.31	0.60	0.56	0.00	0.02	-0.35	0.51
F	4.9	1.3	Yes	0.00	0.08	0.16	0.05	-0.63	-0.45	-0.03
G	4.9	3.8	Yes	0.00	0.35	0.32	0.04	0.62	0.28	0.44
H[§]	0	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[†]Percentage of applied pesticide or nutrient in runoff water. Nutrient recovery adjusted for nutrients recovered in runoff water from treatment H.
[‡]Treatment C = no buffer; pesticides and nutrients applied.
[§]Treatment H = no buffer; no pesticides and nutrients applied.

Table 5. Time to start of runoff and total volume of runoff water for treatments in the August 1995 simulated rainfall event.

Treatment	Buffer Length	Buffer Height	Aerification	Time to start of Runoff Mean	Time to start of Runoff SD	Runoff Volumne Mean	Runoff Volumne SD
	(m)	(cm)		(min)	(min)	(L)	(L)
A	4.9	1.3	No	22.2	10.50	819	220
B	4.9	3.8	No	15.9	7.88	776	265
C†	0	-	-	14.9	14.00	561	263
D	2.4	1.3	No	10.8	6.51	728	210
E	2.4	3.8	No	13.1	9.73	526	318
F	4.9	1.3	Yes	17.1	8.87	704	361
G	4.9	3.8	Yes	20.6	2.29	696	100
I‡	0	-	-	17.2	14.10	498	262

†Treatment C = no buffer; pesticides and nutrients applied.
‡Treatment I = same as treatment C except for application of sulfur-coated urea and chlorpyrifos wettable powder formulations.

Table 6. Concentration and tests of significance for comparisons of the effect of management practices on concentration of pesticides and nutrients recovered in runoff water in the August 1995 simulated rainfall event.

				Pesticide Concentration				Nutrient Concentration		
Treatment	Buffer Length	Buffer Height	Aerification	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
	(m)	(cm)				($\mu g\ L^{-1}$)			($mg\ L^{-1}$)	
A	4.9	1.3	No	5.58	83.80	48.3	0.00	3.01	2.19	3.35
B	4.9	3.8	No	9.65	160.00	90.6	9.11	3.16	2.17	3.87
C†	0	-	-	10.80	174.00	97.8	37.20	5.08	2.02	6.52
D	2.4	1.3	No	9.70	154.00	89.4	7.48	3.86	1.92	6.06
E	2.4	3.8	No	8.26	99.80	59.7	0.00	4.11	2.01	4.83
F	4.9	1.3	Yes	5.67	77.80	43.4	0.00	2.89	2.16	4.01
G	4.9	3.8	Yes	7.32	107.00	62.1	0.00	3.27	2.21	4.47
I‡	0	-	-	9.82	166.00	88.1	20.70	1.83	1.62	8.14

COMPARISONS	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
Buffer Mowing Height (1.3 vs. 3.8 cm)	NS	NS	NS	NS	**§	NS	**
A vs. B	*	*	*	NS	NS	NS	*
D vs. E	NS	NS	NS	NS	NS	NS	NS
F vs. G	NS	NS	NS	NS	**	NS	**
Buffer Length (2.4 vs. 4.9 m)	NS	NS	NS	NS	*	NS	NS
A vs. D	NS	NS	NS	NS	NS	NS	NS
B vs. E	NS	NS	NS	NS	NS	NS	NS
Buffer Length (0 vs. 2.4 m)							
C vs. D	NS	NS	NS	**	**	NS	NS
C vs. E	NS	NS	NS	**	NS	NS	NS
Buffer Length (0 vs. 4.9 m)							
C vs. A	NS	NS	NS	**	**	NS	**
C vs. B	NS	NS	NS	**	**	NS	NS
C vs. F	*	*	*	**	**	NS	**
Aerification (yes vs. no)	NS	NS	NS	NS	NS	NS	NS
A vs. F	NS	NS	NS	NS	NS	NS	NS
B vs. G	NS	NS	NS	NS	NS	NS	NS
Control							
I vs. C	NS	NS	NS	*	**	*	NS

†Treatment C = no buffer; pesticides and nutrients applied.
‡Treatment I = same as treatment C except for application of sulfur-coated urea and chlorpyrifos wettable powder formulations.
§*,** Significant at alpha levels 0.05 and 0.01, respectively. NS=Not Significant.

Table 7. Mass and tests of significance for comparisons of the effects of management practices on mass of pesticides and nutrients recovered in runoff water in the August 1995 simulated rainfall event.

				Pesticide Mass				Nutrient Mass		
Treatment	Buffer Length	Buffer Height	Aerification	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
	(m)	(cm)		(μg)				(mg)		
A	4.9	1.3	No	4450	67900	39400	0	2530	1800	2670
B	4.9	3.8	No	8580	142000	80500	7380	2450	1650	3030
C[†]	0	-	-	6170	97500	56500	18700	2770	1070	3600
D	2.4	1.3	No	6640	106000	61100	4920	2710	1450	4190
E	2.4	3.8	No	5480	72900	44400	0	2340	1060	2890
F	4.9	1.3	Yes	4420	60200	32900	0	1940	1420	2770
G	4.9	3.8	Yes	4790	72500	42000	0	2230	1530	3060
I[‡]	0	-	-	4940	86500	45900	10300	933	791	4610
COMPARISONS										
<u>**Buffer Mowing Height (1.3 vs. 3.8 cm)**</u>				NS	NS	NS	NS	NS	NS	NS
A vs. B				*[§]	NS	NS	NS	NS	NS	NS
D vs. E				NS	NS	NS	NS	NS	NS	NS
F vs. G				NS	NS	NS	NS	NS	NS	NS
<u>**Buffer Length (2.4 vs. 4.9 m)**</u>				NS	NS	NS	NS	**	NS	NS
A vs. D				NS	NS	NS	NS	NS	NS	NS
B vs. E				NS	NS	NS	NS	**	NS	NS
<u>**Buffer Length (0 vs. 2.4 m)**</u>										
C vs. D				NS	NS	NS	**	NS	NS	NS
C vs. E				NS	NS	NS	**	NS	NS	NS
<u>**Buffer Length (0 vs. 4.9 m)**</u>										
C vs. A				NS	NS	NS	**	*	NS	NS
C vs. B				NS	NS	NS	*	**	NS	*
C vs. F				NS	NS	NS	**	*	NS	NS
<u>**Aerification (yes vs. no)**</u>				NS	NS	NS	NS	NS	NS	NS
A vs. F				NS	NS	NS	NS	NS	NS	NS
B vs. G				NS	NS	NS	NS	NS	NS	NS
<u>**Control**</u>										
I vs. C				NS	NS	NS	NS	*	**	NS

[†]Treatment C = no buffer; pesticides and nutrients applied.
[‡]Treatment I = same as treatment C except for application of sulfur-coated urea and chlorpyrifos wettable powder formulations.
[§]*,** Significant at alpha levels 0.05 and 0.01, respectively. NS=Not Significant.

Table 8. Percent recovery of pesticides and nutrients in the August simulated rainfall event.

				Recovery in Runoff Water						
				Pesticides				Nutrients		
Treatment	Buffer Length	Buffer Height	Aerification	Dicamba	2,4-D	Mecoprop	Chlorpyrifos	NH_4-N	NO_3-N	PO_4
	(m)	(cm)				(%)†			(%)	
A	4.9	1.3	No	4.2	6.8	7.3	0.00	5.8	4.1	6.1
B	4.9	3.8	No	7.8	14.2	15.0	0.37	5.6	3.8	6.9
C‡	0	-	-	5.6	9.8	10.0	0.94	6.3	2.4	8.2
D	2.4	1.3	No	6.0	11.0	11.0	0.25	6.2	3.3	9.5
E	2.4	3.8	No	5.0	7.3	8.2	0.00	5.3	2.4	6.6
F	4.9	1.3	Yes	4.0	6.0	6.1	0.00	4.4	3.2	6.4
G	4.9	3.8	Yes	4.4	7.2	7.8	0.00	5.1	3.5	7.0
I§	0	-	-	4.5	8.6	8.5	0.52	2.1	1.8	10.0

†Percentage of applied pesticide or nutrient in runoff water. Nutrient recovery was not adjusted for pre-existing nutrients.

‡Treatment C = no buffer; pesticides and nutrients applied.

§Treatment I = same as treatment C except for application of sulfur-coated urea and chlorpyrifos wettable powder formulations.