Loss of Pendimethalin in Runoff and Leaching from Turfgrass Land under Simulated Rainfall

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A field study was undertaken to investigate runoff and leaching loss of the herbicide pendimethalin in turfgrass land of loamy sand soil. A series of plots constructed in a golf course fairway were surface-applied with pendimethalin SC formulation at the rate of 2.25 or 4.50 kg a.i./ha and subjected to simulated rainfall at 2.0 cm/day for 10 consecutive days. Runoff losses of pendimethalin were the highest at the first rainfall and then gradually decreased with time. The first runoff event contained pendimethalin in its highest concentration, and in subsequent runoff samples the concentration decreased exponentially. The ranges of pendimethalin concentration were 80.9−18.2 and 177.4−48.6 μg/L in the standard and double doses, respectively. Total losses by 20 cm of rainfall for 10 days reached 0.81 and 1.22% of the initial deposits at 2.25 and 4.50 kg a.i./ha, respectively. Pendimethalin concentration in the leachate collected at 30-cm soil depth was quite lower than that in the runoff, and the concentration rapidly decreased from 4.3−4.7 to 0.2−0.4 μg/L during the 10 days of rainfall treatment. Soil residue analysis at 45 and 90 days after pendimethalin treatment showed that more than 90% of the residue remained at the top 10 cm of soil depth. Low runoff and leaching confirmed that lateral and downward movement of the herbicide should be limited in turf soil. The half-life of pendimethalin under field conditions was 23−30 days and was not affected by application dose and rainfall treatment, but longer persistence was observed under laboratory conditions. Considering low runoff and leaching, as well as relatively short persistence in soil, it is concluded that little environmental carryover of pendimethalin would be expected in turfgrass land.

Keywords: *Golf course; herbicides; leaching; pendimethalin; runoff; turfgrass*

INTRODUCTION

Off-target movement of herbicides from agricultural lands and their impact on the environment are growing public concerns. Although agriculture is the largest user of pesticides, turfgrass is typically the most intensively managed biotic system (Walker et al., 1990). Turfgrass of high quality and uniform playing surface has become the expected necessity on golf courses, and this condition often requires the intensive use of pesticides to control pests and weeds. On golf course fairways pesticides are used on a relatively large scale, and higher runoff and leaching potential can be expected due to the hilly and grassy vegetation and sandy soil characteristic. There are many debates on the fate of pesticides applied on golf courses and the impacts of pesticides on nearby ecosystems (Balogh and Anderson, 1992; Balogh et al., 1992). The fate and transfer pathways of pesticides applied to croplands or turfgrass are complex, requiring a broad knowledge of their chemical properties, their transformations, and the physical transport process. Transformations and transport are strongly influenced by site-specific conditions and management practices (Cheng, 1989; Flury, 1996). However, in Korea, limited research has been conducted on the fate of pesticides in turfgrass, and the public concern related to hazardous environmental impacts of the pesticides is one of the most important obstacles to golf course management and construction.

Pendimethalin [*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] is a preemergence dinitroaniline herbicide (Figure 1) which is commonly used to control annual grassy weeds, smooth crabgrass, goosegrass, and annual bluegrass in turfgrass environments. Pendimethalin is characterized by low water solubility (0.3 mg/L at 20 °C), moderate to high vapor pressure (4.0 mPa at 25 °C), and strong adsorption to soil ($K_{oc} = 7011$ mL/g in loamy sandy soil of 0.87% OC) (Tomlin, 1997; US EPA, 1997). This herbicide is known to be strongly adsorbed onto soil and organic matter, possibly due to its high potential for hydrogen bonding (Weber, 1990), resulting in a decrease in mobility and bioavailability of this compound. The movement of this herbicide in surface runoff and leaching is expected to be low except where soil erosion results in sediment transport of adsorbed herbicide (Starrett et al., 1996; Suzuki, 2000; Traub-Eberhand et al., 1995).

In 1999, total consumption of pendimethalin for field crops in Korea was 118 900 kg of active ingredient (a.i.) in 200 000 ha. This herbicide was introduced into golf courses in Korea for the first time in 1999, and the total usage was 1125 kg a.i. in 500 ha (ACIA, 2000). Total golf course area in Korea that is treated with herbicides is 7300 ha, and the consumption of pendimethalin for golf courses is expected to increase significantly in near future.

Although pendimethalin itself has low water solubility and high adsorption characteristics, the potential environmental loss, particularly when used in a formu-

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10.1021/jf0005869 CCC: $19.00

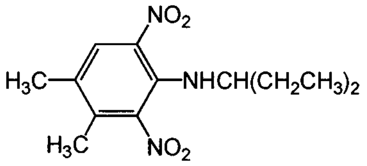

Figure 1. Chemical structure of pendimethalin.

Table 1. Physicochemical Characteristics of the Soil

	soil separate (%)				OM	CEC	FMC[a]
texture	sand	silt	clay	pH	(%)	(cmol/kg)	(%)
loamy sand	77.5	13.4	9.1	5.7	2.2	5.5	17.7

[a] FMC, field moisture capacity, measured at 0.1 bar.

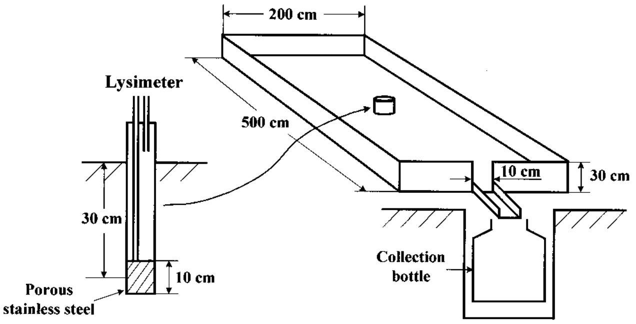

Figure 2. Diagram of the field plot design.

lation such as suspension concentrate containing a large amount of dispersing agent, should be evaluated before widespread use. In any management system, rainfall can reduce the efficacy of pesticides by decreasing the availability of pesticide for target uptake by causing pesticide runoff and leaching when applied to soil. The extent of herbicide runoff and leaching loss is essential information for optimizing weed management and reducing the potential impacts on the ecosystem around the application site. In lieu of full-scale field experiments that are difficult and time-consuming, simulated rainfall applied to small field plots can provide useful data.

The objective of this study was to evaluate the potential environmental carryover and persistence of pendimethalin in field plots of golf course fairways under simulated rainfall.

MATERIALS AND METHODS

Field Experiment. The experiment was conducted on the fairway of the seventh hole of the east course in Taegu Country Club, Kyongsan, Korea. The soil was a Taegu loamy sand (nonacidic, mesic, Lithic Eutrocherepts) which generally has a moderate hydraulic conductivity. Physicochemical characteristics of the soil are provided in Table 1. The climate in this region is temperate, with annual mean temperature and precipitation approximately 15 °C and 1200 mm, respectively. Eight plots were constructed on the fairway, which was covered with turfgrass (*Zoysia japonica* Steud). The site had a natural slope of 8−9%. Unit plot size was 10 m^2 (5 m × 2 m), and a buffer zone wider than 1 m was installed to prevent plots from cross contamination. Each plot was enclosed with polyethylene plates, 40 cm high with the bottom 10 cm of the plate buried in the soil, to direct the runoff water within the plot. A ditch was dug at the lower end of each plot to collect runoff water. To collect the leaching water, a lysimeter (SW-070, Soil Measurement Systems Co., Tucson, AZ) was installed in the center of each plot at a 30-cm depth. A schematic diagram of an experimental plot is presented in Figure 2. The plots were initially mowed at a 4-cm cutting height and undisturbed during the remainder of the experiment.

Pendimethalin (45% suspension concentrate (SC), Shaft) was applied once on April 20, 1999 at standard and double rates of 2.25 and 4.50 kg a.i./ha, respectively. Practically, the calculated amount of pendimethalin SC formulation, 5 or 10 mL per plot, was diluted to 5 liters and broadcast on the turf soil surface using a backpack-type manual sprayer (20-L capacity) in the usual manner. Each treatment was duplicated.

Simulated rainfall of 20 mm was applied each day (200 L/plot) using tap water at an intensity of 40 mm/h during 10 consecutive days starting from 1 day after pesticide application. This application was done by using a spreader type nozzle system operated at 20 kPa at a 0.5-m height. A total 200 mm of rainfall was applied during the 10 days. This amount of rainfall is approximately equal to the sum of the average rainfall from March until May in this region. A treatment with no rainfall was included in this study as a control to determine the residual pesticide in the soil.

Sampling. Runoff water samples were collected during the rainfall application from the ditch located at the lower end of each plot. The runoff water in each plot was quantified and a 200-mL portion of subsample was retained for pendimethalin analysis. Forty to 60 mL of leaching water samples were collected from the lysimeters installed in the plots 1 h after rainfall application. The water sample was filtered using Toyo No. 6 filter paper and subjected to the pendimethalin analysis on the same day as the sampling.

Field soil samples were collected at 1, 10, 20, 30, 45, 60, and 90 days after the pendimethalin application. Ten soil core samples were collected in each plot from the top 10 cm using a soil sampler (bi-partite gouge auger with a cylindrical tapered cutting head, 2.5 cm i.d.). Additionally, four soil core samples were taken in each plot at depths of 0−10 and 10−20 cm using a cylindrical core sampler (10 cm i.d. x 20 cm H) at 45 and 90 days after the pesticide application to determine downward movement of the pendimethalin in the soil. These samples were taken to the laboratory immediately after collection. Cores collected from each plot were gently crushed and combined to form one soil sample per plot. After drying for 5 h at room temperature, each combined soil sample was mixed thoroughly in a polyethylene bag by hand and passed through a 2-mm sieve. Soil samples were stored in polyethylene bags at −20 °C until the time of herbicide residue analysis.

Persistence under Laboratory Conditions. Laboratory persistence of pendimethalin was also investigated. A bulk sample of control soil was collected at the top 10-cm depth from the experimental field, air-dried, and passed through the 2-mm sieve before use. Each 500-g (oven-dry basis) portion of the control soil was evenly spread on a stainless steel dissecting pan. Pendimethalin standard solution, 200 or 400 mg/L in acetone, was carefully treated dropwise on the soil surface to yield the herbicide concentration of 2.25 or 4.50 mg/kg. The organic solvent was evaporated in a ventilated hood for 1 h at room temperature with continuous stirring of the soil using a stainless steel spatula. The treated soil was thoroughly mixed in a V-blender for 30 min and weighed into wide-mouth test tubes (27 mm i.d. × 17 cm H) by 20-g portion per tube. Distilled water was added to adjust the moisture content equivalent to 60% field moisture capacity at 0.1 bar, and then contents in the tube were briefly mixed. Each tube was loosely covered with aluminum foil and incubated at 25 ± 1 °C. Water lost by evaporation was about 0.5 mL on average each week and the loss was replenished with distilled water every week during the experiment. Two tubes were taken at 1, 10, 20, 30, 60, 90, 150, and 180 days after treatment, sealed tight with silicon stoppers, and stored at −20 °C until analyzed.

GLC Analysis of Pendimethalin. *Chemicals.* Analytical standard of pendimethalin (98.4% pure) was kindly supplied by American Cyanamid Co. (Parsippany, NJ). Stock standard solution of 1000 mg/L was prepared in acetone and was stable at 4 °C for a minimum of six months. A working solution was prepared in appropriate solvents whenever necessary. All the solvents were pesticide residue grade or reagent grade freshly redistilled in glass. Florisil (60−100 mesh, pesticide residue grade) was purchased from Aldrich Chemical (Milwaukee, WI), and activated at 130 °C for more than 5 h prior to use. All other reagents were reagent grade unless specified.

Extraction and Cleanup. A 20-g portion of soil sample (oven-dry basis) was moistened with 20 mL of distilled water. The moistened soil sample was left standing for 10 min, then 100 mL of acetone was added, and the sample was extracted for 1 h on a gyrotatory shaker at 200 rpm. The mixture was suction-filtered through a filter paper (Toyo No. 6, Japan) on a porcelain Büchner funnel. The cup and filter cake were washed with 30 mL of fresh acetone, and the rinsate was combined with the previous filtrate. The volume of filtrate was adjusted to 150 mL with acetone, and mixed for 30 s by hand. One-fifth aliquot, equivalent to 4 g of soil, was quantitatively transferred into a 250-mL separatory funnel. The sequential addition of 30 mL of *n*-hexane, 10 mL of saturated NaCl, and 100 mL of distilled water was followed. The resulting sample was vigorously shaken for 1 min and let stand until two layers clearly separated; the lower aqueous phase was discarded. The hexane phase was dried over 20 g of anhydrous sodium sulfate layer, and evaporated just to dryness in vacuo at 40 °C. The residue was dissolved in 10 mL of *n*-hexane and subjected to Florisil column chromatography.

To a portion of water sample, typically 100 mL, placed in a 250-mL separatory funnel, 30 mL of *n*-hexane and 10 mL of saturated NaCl were added. Pendimethalin was partitioned into the hexane phase, in a manner identical to the soil sample, and subjected to Florisil column chromatography.

A chromatographic column (11 mm i.d. × 40 cm) was plugged with glass wool, dry-packed with 5 g of activated Florisil, and topped with ca. 2-cm layer of anhydrous sodium sulfate. The column was pre-washed by passing 25 mL of *n*-hexane until the solvent level reached the top of the sodium sulfate layer. The hexane extract from the partition step was poured into the column and the column wall was rinsed twice with 2-mL portions of *n*-hexane. When the liquid drained to the sodium sulfate layer, the column was eluted with 50 mL of dichloromethane/*n*-hexane mixture (20/80, v/v), and the fraction was discarded. The column was then eluted with 50 mL of dichloromethane/acetonitrile/*n*-hexane mixture (50/0.35/49.65, v/v/v), the collected eluate was concentrated just to dryness, and the residue was reconstituted with 10 mL of *n*-hexane for GLC determination.

Gas−Liquid Chromatography (GLC). A Hewlett-Packard (HP, Palo Alto, CA) model 6890 gas chromatograph, equipped with packed inlet, ^{63}Ni-electron capture detector (ECD), a capillary column SPB-5 (30 m × 0.53 mm i.d.), 0.5 μm film (Supelco Inc.), and HP 3396 Series II integrator, was used for pendimethalin determination. Operating parameters were column temperature, 180 °C; detector temperature, 300 °C; inlet temperature, 270 °C; sample size, 2 μL; and chart speed, 0.5 cm/min. Helium and nitrogen were used as carrier and makeup gas at 15 and 50 mL/min, respectively. Under these conditions, retention time of pendimethalin was 5.1 min.

Validation of the Analytical Method. Recovery experiments were run on the control soil and water samples to validate the analytical method proposed for the pendimethalin residue. Prior to extraction, a series of control samples were fortified with pendimethalin standard solution in acetone at specified concentrations. After the samples were left standing for 2 h, the analytical procedures mentioned above were carried out to produce quality assurance data. This validation procedure was also used periodically to confirm the method performance during the experiment.

RESULTS AND DISCUSSION

During the treatment of simulated rainfall there was only 3 mm of natural rainfall on the ninth day of the rainfall treatment, and runoff did not occur with this event. After the simulated rainfall treatment, there were 18 events of natural rainfall which totaled 353 mm during the remaining period of the experiment. The temperature was in the range of 12 to 29 °C.

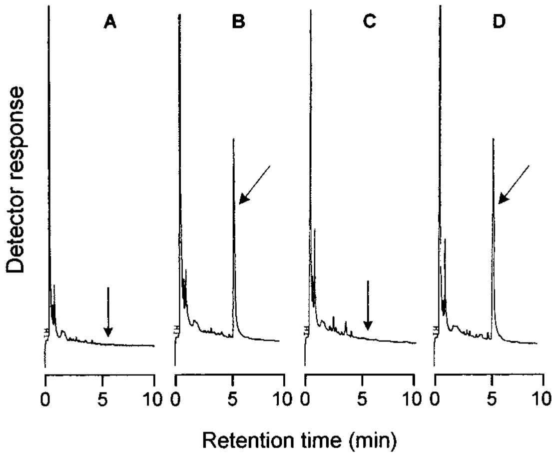

Figure 3. Typical GLC chromatograms of pendimethalin in soil and water extracts. (A) control soil; (B) soil sample at 0.1 mg/kg; (C) control water; (D) water sample at 0.004 mg/L. The arrow indicates the peak or peak position of pendimethalin.

Table 2. Recovery and Detection Limit of Pendimethalin in GLC Analysis

sample	fortification[a]	recovery[b]± SD (%)	detection limit[a]
soil	0.1	91.8 ± 2.1	0.005
	1.0	93.2 ± 4.3	
water	0.004	106.2 ± 4.3	0.0002
	0.1	103.0 ± 7.0	

[a] Units: mg kg^{-1} and mg L^{-1} for soil and water samples, respectively. [b] Mean values for triplicate samples with standard deviation.

Method Efficiency. Typical GLC chromatograms of soil and water extracts are shown in Figure 3. The method produced clean chromatograms free of interference. Detection limits were 5 μg/kg for soil and 0.2 μg/L for water samples based on 5% full-scale deflection (S/N >10). These sensitivities were sufficiently high to track the behavior of pendimethalin in the turf soil environment considering the normal application rate of the herbicide (2.25 kg a.i./ha). Percent recoveries generated during the validation of analytical methods are presented in Table 2. Recoveries averaged 104.6 ± 5.4% (n = 6) and 92.5 ± 3.0% (n = 6) for soil and water samples, respectively. Relative standard deviations over both types of samples were less than 10%, indicating that the method could be reproducibly applied to the analysis of pendimethalin residues in soil and water samples.

Surface Runoff. Considering 20 mm of rainfall was applied 1 day before the herbicide application, soil moisture was about 20% at the point of the initial runoff experiment. Typically the runoff would start about 10 min after the onset of rainfall and end about 20 to 30 min after the rain had stopped. Total runoff water volumes were in the range of 37.5 to 78.5 L in the plots, and the average was 51.9 L. This result means that 18.8 to 39.3% (average 26.0%) of rainfall applied was lost as runoff. Sediment loss in runoff water was small (<0.05 g/L) at this site with dense and thick turfgrass. Because a much greater amount of the pesticide was expected to be present in the water, loss of pendimethalin with sediment in runoff was not considered in this experiment.

Figure 4 illustrates the concentration pattern of pendimethalin in total runoff of each event. The first runoff event contained the herbicide in its highest concentration, and contained pendimethalin at 80.9 and 177.4 μg/L in the standard and double doses, respec-

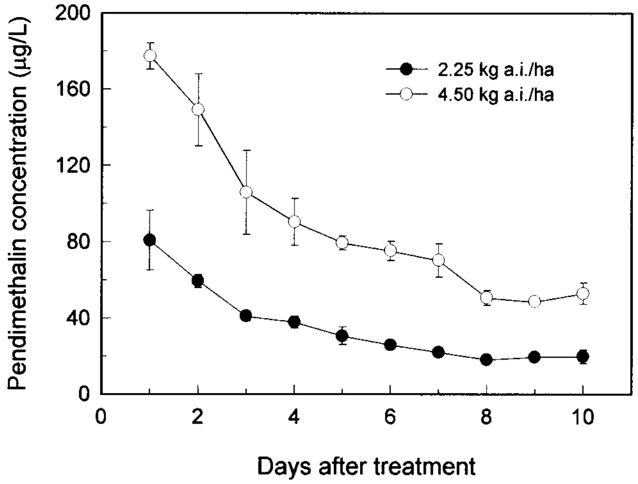

Figure 4. Concentration of pendimethalin in runoff from turfgrass land surface under simulated rainfall. Data points are the means of duplicate samples and error bars denote the ranges.

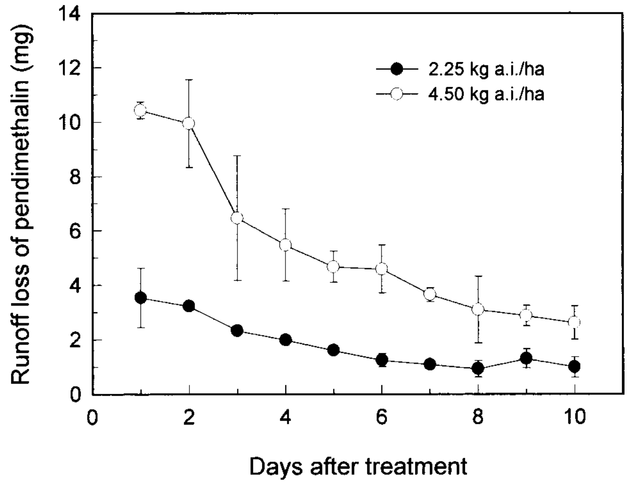

Figure 5. Daily loss of pendimethalin in runoff from turfgrass land surface under simulated rainfall. Data points are the means of duplicate samples and error bars denote the ranges.

tively. Cole et al. (1997) found 314 µg/L of 2,4-D, 164 µg/L of mecoprop, and 34.8 µg/L of chlorpyrifos in 64 L of runoff collected from a bermudagrass turf (6% slope) where 83 mm of simulated rainfall was applied with 51 mm/h of intensity within 24 h of application of the pesticides. Dithiopyr, like pendimethalin, has a high potential for retention within the thatch, mat, and surface soil, and its solubility in water is 1.38 mg/L and K_{oc} is 1920 (Schleicher et al., 1995). In a simulated golf course fairway, Hong and Smith (1997) investigated the potential surface movement of dithiopyr applied in the rate of 0.56 kg a.i./ha as an EC formulation. When they applied 38 mm of simulated rainfall on the first day after treatment, concentration of the herbicide in runoff was 39.27 µg/L. Although the pendimethalin concentration found in the runoff of our study is lower when compared to concentrations of the highly soluble pesticides (2,4-D and mecoprop), it was much higher than the concentrations of chlorpyrifos and dithiopyr, which have relatively low solubility in water and high adsorption affinity. However, considering the application rate and formulations of those pesticides, and the rainfall treatments, the concentrations of chlorpyrifos and dithiopyr in runoff could be as high as the pendimethalin concentration in runoff of our study. The high concentration of pendimethalin in runoff found in this study could be mainly due to the extreme condition of rainfall intensity and timing. Slope of the plot and use of the SC formulation containing a large amount of dispersing agent could be other factors for the significant loss.

Pendimethalin concentrations in subsequent runoff samples decreased exponentially. Thus, after the first rainfall, the remaining pesticides seemed to be tightly adsorbed on the surface of the turfgrass and soil. Loss by volatilization and degradation is another factor for the reduced runoff loss of pendimethalin in the later rainfall events. Half-lives of pendimethalin in field conditions are relatively short (Barrett and Lavy, 1983; Schleicher et al., 1995; Zimdahl et al., 1984) and volatile losses of pendimethalin during the 48 h following application totaled 6.1%, with an estimated loss of approximately 13% during the 5-day period following application (Cooper et al., 1990). In many studies the pesticide runoff was greatest when the rainfall occurred immediately after pesticide application and was intense (Smith and Bridges, 1996; Southwick et al., 1993).

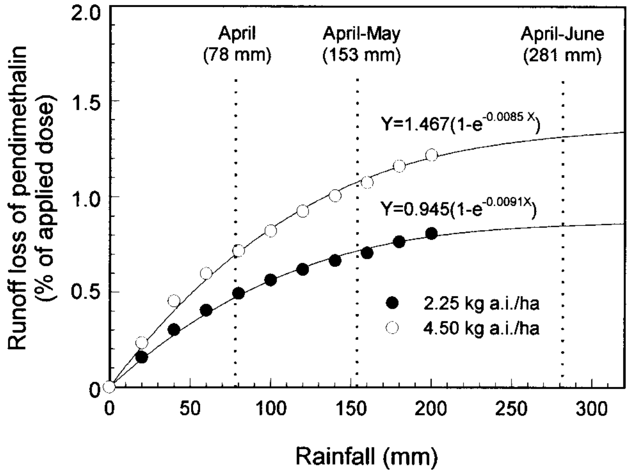

Figure 6. Cumulative loss of pendimethalin in runoff from turfgrass land surface as a function of the applied simulated rainfall. The dotted line indicates the average natural rainfall on the experimental site during the designated period.

Daily and cumulative losses of pendimethalin in runoff are illustrated in Figures 5 and 6. In the first runoff event after treatment, 0.16 and 0.23% of applied pendimethalin were lost with runoff for the standard and double doses, respectively. After this, the subsequent losses decreased exponentially. During the 10 days of rainfall treatment, total losses of pendimethalin in the standard and double doses amounted to 18.2 and 54.8 mg, respectively. Compared to the standard rate, daily and cumulative losses were about 3 times higher for the double application rate. And the total fractions of the applied pendimethalin leaving the plots by runoff were 0.81 and 1.21% in the standard and double doses, respectively. Considering sediment loss in runoff was negligible in this study, most of the pesticide loss in runoff is likely to be in the dissolved phase. Loss of sediment and surface runoff from established turfgrass is limited compared to that of agricultural systems (Balogh and Watson, 1992; Gross et al., 1991). In croplands where the sediment load could be greater, pendimethalin loss in runoff would be higher than that reported in the results of this study. Gouy et al. (1999) found that, when the pesticide was applied onto bare soils of sandy loam, 14% of total trifluralin applied was

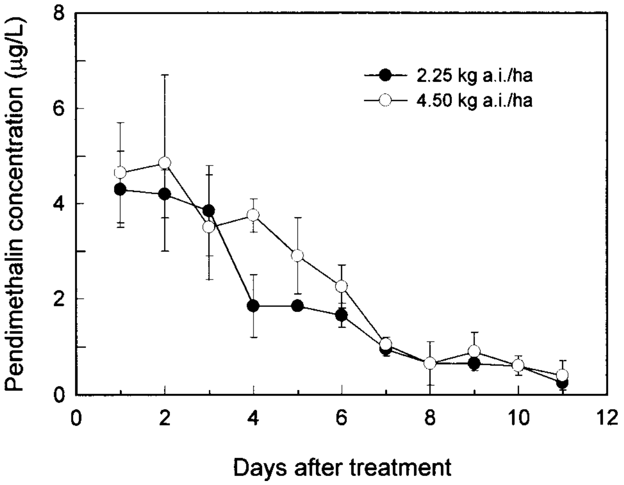

Figure 7. Pendimethalin concentration in rainwater collected at the depth of 30 cm in turfgrass land under simulated rainfall. Data points are the means of duplicate samples and error bars denote the ranges.

lost in runoff and 90% of that lost was adsorbed onto eroded particles.

Although experimental conditions were different from those of our study, Smith and Bridges (1996) found in simulated golf course fairways that the total runoff losses were 8.9, 14.0, and 12.8% of initial deposits for 2,4-D, dicamba, and mecoprop, respectively. However, in another study, less than 2.0% of the dithiopyr applied in a golf course fairway of 5% slope was transported from the plots under 188 mm of rainfall treatment in 11 days after the herbicide application (Hong and Smith, 1997). Considering these results, the characteristics of pendimethalin having low solubility, strong adsorption, high vapor pressure, and easy photodegradation would be the factors that could limit runoff loss of pendimethalin in turfgrass land (Jacques and Harvey, 1979; Pal et al., 1991; Schleicher et al., 1995; Weber, 1990).

The results of this study reflect the runoff potential of pendimethalin under a very severe case in terms of the amount and timing of rainfall. Therefore, the runoff loss of pendimethalin in golf course fairways under normal climate conditions in the region is expected to be much lower than those found in this study. As shown in Figure 6, normal rainfall in April through June in the region is 281 mm. And even though this amount of rainfall is concentrated in the first 10 days after pendimethalin application, runoff loss of the pesticide would be less than 1.0% of the initial deposit with the standard application rate.

Leaching with Percolating Water. Pendimethalin concentrations in the leaching waters collected at the 30-cm soil depth are shown in Figure 7. With the standard pesticide-application rate, the first leaching water contained the herbicide in its highest concentration of 4.3 μg/L, and then a steady decrease in concentration occurred over the remainder of the study. In the case of double dose application, the highest concentration of pendimethalin in leaching water was found in the second rainfall event. In this case, the rainfall caused more residues of pendimethalin to move downward before substantial adsorption occurred. But the concentrations of pendimethalin in leaching waters were not significantly different between the two application rates. During the first 7 days after treatments, the concentration decreased rapidly down to around 1 μg/L and then more slowly below 1 μg/L level. Suzuki (2000) also found pendimethalin concentration at a low level (<1 μg/L) in the leachate collected at 10−50-cm depth after 15 and 22 days of the application in upland field under natural rainfall.

Table 3. Distribution of Pendimethalin Residues by Soil Depth

days after treatment	rainfall	pendimethalin residue[a] (mg/kg) 0−10 cm	pendimethalin residue[a] (mg/kg) 10−20 cm	relative distribution at top 10 cm (%)
		2.25 kg a.i./ha		
45	yes	0.616	0.036	94.5
	no	0.447	0.025	94.7
90	yes	0.189	0.021	90.0
	no	0.117	0.005	95.9
		4.50 kg a.i./ha		
45	yes	0.912	0.063	93.5
	no	0.621	0.063	90.8
90	yes	0.190	0.014	93.1
	no	0.289	0.010	96.7

[a] Mean of duplicate samples.

Because leaching water volume was not measured, total leaching loss of pendimethalin could not be determined. A rough leaching loss of pendimethalin was estimated from the following calculations. Considering 26%, on average, of the applied rainfall was lost through surface runoff during the 10 days of rainfall application, a maximum total of 1500 L of rainfall could leach down below 30-cm soil depth in each plot. And, as the average concentrations of pendimethalin in leaching water were 1.9 and 2.3 μg/L at standard and double doses of the herbicide, respectively (Figure 7), total pendimethalin losses through leaching, at maximum, could be 2.85 and 3.45 mg in each plot. These amounts of the pesticide are the equivalent of 0.13 and 0.15% of the initial doses of the standard and double applications, respectively. Compared to the loss in surface runoff, leaching loss of pendimethalin is expected to be much smaller (<16% of runoff loss).

The concentrations of pendimethalin in the leaching waters were relatively low, and the potential leaching loss of the herbicide applied to established turfgrass land and its environmental impacts are expected to be very limited. And, when this leaching water is mixed in groundwater or surface water systems, the potential hazardous effects would be further reduced. Starrett et al. (1996) investigated the movement of pesticides under different irrigation regimes using 50-cm long undisturbed soil columns. They found only 0.2% of the applied pendimethalin in leachate from soil columns even under heavy irrigation. Stahnke et al. (1991) also found very small leaching loss of pendimethalin in a 150-cm high rhizotron packed with silty clay loam soil.

To find out downward movement of pendimetalin in soil, core samples were taken at the depth of 10 to 20 cm at 45 and 90 days after the herbicide treatment, and the results are shown in Table 3. Although generally higher concentrations of pendimethalin were found in deeper soil in the rainfall treatments, pendimethalin detected at this depth did not represent a significant fraction of the total amount applied. This result indicates that downward movement of pendimethalin in the soil is very limited with the strong adsorption on soil mineral particles and organic materials. The surface layer of organic matter was thick (6.5 cm). Dinitroaniline herbicide molecules contain moieties, which readily form hydrogen bonds with soil organic matter

Table 4. Half-Life of Pendimethalin in Turfgrass Soil under Field and Laboratory Conditions

condition	applied dose (kg a.i./ha)	rainfall	equation[a]	R	half-life (days)
field	2.25	yes	$R = 1.495 \bullet e^{-0.0235T}$	0.949^{**}	29.5
		no	$R = 1.628 \bullet e^{-0.0291T}$	0.987^{**}	23.8
	4.50	yes	$R = 3.124 \bullet e^{-0.0302T}$	0.993^{**}	23.0
		no	$R = 3.041 \bullet e^{-0.0294T}$	0.970^{**}	23.6
laboratory	2.25	-	$R = 2.410 \bullet e^{-0.0108T}$	0.969^{**}	64.2
	4.50	-	$R = 4.496 \bullet e^{-0.0058T}$	0.969^{**}	119.5

[a] First-order kinetics.

and decrease leaching and bioactivity (Weber, 1990). Pederson et al. (1995) found that the partition coefficient, K_d value, between soil and water was in the range of 2.23 to 1638, and the value increased with increasing amount of organic carbon in soil. Therefore, the thick thatch layer could be an important factor for the limited downward movement of pendimethalin in turfgrass. Stahnke et al. (1991) found that most of the pendimethalin applied to Kentucky bluegrass turf remained in the thatch and 0- to 2.5-cm soil depth. Schleicher et al. (1995) also found a limited downward movement of pendimethalin in perennial ryegrass turf. These results are consistent with the very low leaching loss of pendimethalin discussed earlier in this study.

Persistence in Soil. Persistence of pendimethalin in the turfgrass soil is summarized in Table 4. The dissipation pattern of pendimethalin in soil was interpreted as first-order kinetics. The values of the regression coefficient (R) were all found to be significant at the 1% error level. Half-life, defined as the time required for 50% reduction of the initial residue level, was calculated from the exponential regression of residue data. The half-lives of pendimethalin were found to be shorter than 30 days in the field conditions. In comparison to other studies (Gasper et al., 1994; Tsiropoulos and Miliadis, 1998; Zimdahl et al., 1984), the half-life of pendimethalin determined in this study was shorter. Hurton et al. (1979) have reported more rapid degradation of dinitroaniline herbicides in thatch than in soil due to the higher microbial activity in thatch. Vapor loss of pendimethalin could be much higher when applied on turfgrass due to the high vapor pressure of the pesticide. Walker and Bond (1977) reported that when pendimethalin was incorporated after application in April, more than 60% remained in September, but only 20% remained when the herbicide was not incorporated. And, the half-lives were not significantly different between the two application rates. This result indicates an independence of the degradation rate from the application dose, which is consistent with other results (Zimdahl et al., 1984; Walker and Bond, 1977; Tsiropoulos and Miliadis, 1998). Although soil moisture can affect pesticide degradation (Barrett and Lavy, 1983), rainfall application in this study did not change the half-life of pendimethalin. In all treatments, at 90 days after treatment less than 10% of the initial deposits remained in the soil.

In the laboratory condition, the half-life was much longer than in field conditions. The half-life was also much longer at double dose. The effect of dose rate was very significant in laboratory conditions. The difference between field and laboratory conditions may be due to the various environmental factors. The rapid degradation of pendimethalin in field conditions can be attributed, in some extent, to the possibility of photodecomposition and volatilization of pendimethalin. Pendimethalin is known to be decomposed readily when irradiated at wavelengths $\lambda \geq 250$ nm by the mechanisms involving oxidative dealkylation, nitro reduction, and cyclization (Dureja and Walia, 1989).

Conclusion. Considering the overall results of this study, a greater portion of pendimethalin retention would be expected in the top 10-cm depth, including thatch, and runoff and leaching losses could be very limited. The data of half-life and vertical distribution of pendimethalin in soil indicated that adsorption and degradation of the herbicide in turfgrass are strong and rapid.

Pendimethalin has been detected in surface water samples at concentrations of <0.001 to 17.6 μg/L in the United States (USEPA, 1997), which is quite lower than the concentration we found in runoff samples collected in field plots. A buffer zone between pesticide application areas and surface water resources could reduce pesticide concentrations in runoff via various dilutions and filtrations, especially for highly adsorbed pesticides (Cole et al., 1997). Also, we need to consider the fact that pesticide runoff from small plots could be overestimated by a factor of up to 2 compared with that from typically larger fields (Wauchope, 1978). Typically, water features surrounding golf courses are not used for drinking water, and perhaps a better indication of the potential for contamination of surface waters on golf courses is the effect on aquatic organisms (Cole et al., 1997). Lethal concentrations (LC_{50}) found to kill 50% of rainbow trout, bluegill sunfish, and channel catfish are 138, 199, and 418 μg/L, respectively, for technical pendimethalin (USEPA, 1997). Although very extreme rainfall conditions were applied in this study, pendimethalin concentration in runoff at the standard application rate was below these critical levels. Pendimethalin is not listed in the Drinking Water Standards and Health Advisories table of USEPA (USEPA, 2000). However, considering that the reference dose value for pendimethalin is 0.05 mg/kg/day, a lifetime health advisory for pendimethalin in drinking water calculated according to USEPA methodology would be 700 μg/L (USEPA, 1993). Therefore, 1−5 μg/L pendimethalin levels in leaching water found in this study are far below levels of toxicological significance.

Therefore, although the fate of pendimethalin would be controlled by various environmental conditions, the present study suggests that the application of pendimethalin SC formulation to golf course fairways would not pose a high risk of groundwater or surface water contamination.

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Received for review May 12, 2000. Revised manuscript received August 30, 2000. Accepted September 5, 2000.

JF0005869