Turfgrass and Environmental Research Online

...Using Science to Benefit Golf

One of the three major objectives of USGA Turfgrass and Environmental Research Program since 1991 is to understand the effects of turfgrass pest management and fertilization on water quality.

Volume 1, Number 3
April 1, 2002

PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 215 projects at a cost of $21 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

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Environmental Research: Past and Future

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SUMMARY

We live in interesting times when the truth and public perception on environmental issues are shaped more by the media and special interest than science and reason. Turfgrass scientists need to look beyond the fairway and understand how the plant species we work with fit in to sustainable, urban landscapes. This paper summarizes past environmental research focused on the fate of pesticides and fertilizers applied to turfgrasses; water quality and quantity issues; and efforts to address public concerns about amenity and recreational turfgrass.

In general, the research shows that under most conditions, the small amounts of pesticides and nutrients that move through the soil are found at levels below the health and safety standards established by the U.S. Environmental Protection Agency. The important components affecting the fate of pesticides and nutrients are a) the filtering properties of the canopy and thatch; b) soil texture; and c) solubility and adsorption properties of the product applied. The paper also looks forward into the future and describes the problems that will face the turfgrass industry and the research needed to address these problems.

Since 1920, the USGA has been dedicated to improving the playing conditions of golf courses in the United States. This single, centralized, not-for-profit agency, free from commercial connections, was a pioneer and remains today a chief authority in turfgrass management for golf. From the control of turfgrass pest problems to the breeding and release of improved turfgrass cultivars for golf, the USGA Green Section has been directly involved in every phase of golf course maintenance and management. The Green Section has been involved in research pertaining to cultural practices, equipment development, soils, sands, fertilizers, irrigation, and other materials and practices used in golf course maintenance.

In the 1970s, people became concerned about howgolf courses affect the environment. A series of widespread droughts during the late 1970s and 1980s, highlighted by a severe drought in California and other western states, caused extreme restrictions on water-use in hundreds of communities. Golf courses were among the first and most severely restricted operations in many areas, due in part to their visibility and because they were considered non-essential users of water.

Similarly, during the golf course construction boom of the 1980s and 1990s, golf courses were again under attack because of their perceived affect on the natural environment. Existing golf courses also were scrutinized because of the perceived misuse of pesticides on the property. In many cases, anti-development groups tossed around unsubstantiated claims about the negative effects of golf courses in an effort to block commercial real estate development associated with the course.

Environmental groups and the media broadly criticized golf courses for polluting water supplies with pesticides and fertilizers, although direct evidence of their contribution was practically non-existent. Nevertheless, scattered incidents of bird and fish kills have occurred, and certainly, the potential for water pollution is there if pesticides and fertilizers are not applied with care. In the late 1980's, the USGA decided to begin investigating this issue, in part, because there was little research with which to respond to criticisms.

Despite the dramatic growth in popularity during the past 20 years, golf still is criticized by people who believe that course maintenance practices have a deleterious impact on the environment. One of the greatest fears is that nutrients and pesticides used to maintain golf courses will pollute drinking water supplies. Many people are concerned about the potential effects of elevated pesticide and nutrient levels on human health.

In addition, there is concern for the ecolo-

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USGA Turfgrass and Environmental Research Online 1(3):1-25.
TGIF Record Number:79123

gy of surface waters and wildlife health problems associated with the use of pesticides and nutrients on golf courses. Claims have been made that up to 100 percent of the fertilizers and pesticides applied to golf course turf end up in local water supplies, a claim with no basis in fact. However, a significant emotional reaction from a scientifically illiterate public, unaware of what happens to chemicals in the environment, has increased the urgency and hysteria surrounding the pesticide and nutrient fate issues.

The Turfgrass Research Program was invigorated in 1983 and continues today. There were three major objectives of this program. First, breed new grasses for golf that use less water and are resistant to pests and stresses. Second, develop maintenance practices that help grasses resist heat, cold, drought, pests, and other stresses. Last, investigate how grasses resist stresses and pests, and use this information in breeding programs.

As an important leadership organization in golf, the USGA initiated a research program focused on environmental issues in 1989. In particular, university research studies examining the effects of fertilizers and pesticides on surface and groundwater resources were initiated. The studies were conducted on the major pathways of chemical fate in the environment, including leaching, runoff, plant uptake and utilization, microbial degradation, volatilization, and other gaseous losses. The studies were conducted at twelve universities throughout the United States, representing the major climatic zones and turfgrass types. The goal of the program was to build a solid foundation for discussing the effects of golf course activities and turfgrass management on the environment (Snow, 1995).

Past Environmental Research

Since 1991, the Environmental Research Program has evaluated the effects of golf courses on people, wildlife and the environment. The three major objectives of the program were to 1) understand the effects of turfgrass pest management and fertilization on water quality; 2) evaluate valid alternative pest control methods; and 3) document the turfgrass and golf courses benefits to humans, wildlife and the environment.

Pesticide and Nutrient Fate Research

Golf course superintendents apply pesticides and fertilizers to the course, and depending on an array of processes, these chemicals break down into biologically inactive by products. There are several interacting processes that influence the fate of pesticides and fertilizers applied to turf. For the purposes of this section, the following seven categories that influence the fate of pesticides and nutrients will be discussed: 1) volatilization, 2) water solubility, 3) sorption, 4) plant uptake, 5) degradation, 6) runoff, and 7) leaching.

The role these processes play in the likelihood that the pesticides will reach ground or surface water will be addressed. The relative importance of each process is controlled by the chemistry of the pesticide or fertilizer and environmental variables such as temperature, water content, and soil type.

Volatilization

Volatilization is the process by which chemicals transform from a solid or liquid into a gas. The vapor pressure of a chemical is the best indicator of its potential to volatilize. Pesticide volatilization increases as the vapor pressure increases. As temperature increases, so do vapor pressures and the chance for volatilization loss. Volatilization losses are generally lower following a late afternoon or an early evening pesticide application rather than in the late morning or early afternoon when temperatures are increasing. Volatilization also will increase with air movement and can be greater from unprotected areas than from areas with windbreaks. Immediate irrigation is usually recommended for highly volatile pesticides to reduce loss.

Nitrogen Volatilization.

Only a few studies have evaluated nitrogen volatilization from turfgrass. Nitrogen volatilization depends on the degree of precipitation or irrigation after the application of fertilizer

(Bowman et al., 1995; Joo et al., 1987; and Joo et al., 1991). As much as 36 percent of the nitrogen volatilized under non-irrigated conditions. A water application of 1 cm reduced volatilization to eight percent.

Miltner et al., (1996) could not account for 36 percent of the nitrogen applied one year after a spring application on Kentucky bluegrass in Michigan. It was suggested that volatilization and denitrification could be responsible. However, in a follow-up study conducted in Illinois on a mature Kentucky bluegrass turf, denitrification accounted for only for 5 to 15 percent of the applied labeled (^{15}N) fertilizer nitrogen (Branham, 2001). Denitrification occurred routinely after rainfall or irrigation events and in large quantities following soluble nitrogen fertilizer applications.

In a greenhouse experiment, Starrett et al. (1995) investigated the fate of ^{15}N applied as urea from intact soil columns (Table 1). Nitrogen recovery averaged 82.4 and 89.7 percent for single (one 25 mm per week) and split (four 6 mm per week) irrigation treatments. Nitrogen volatilization was higher for the split application; however, this difference was not significant.

Pesticide Volatilization.

The volatilization studies determined the amount of several pesticides that volatilized into the air for several days after application (Table 2). Reported volatile losses over a one to four-week period, expressed as a percentage of the total applied, ranged from less than one percent to 16 percent (Cooper et al., 1995; Murphy et al., 1996a; Murphy et al., 1996b; Snyder and Cisar, 1996; Yates et al., 1996; Yates, 1995). Results of volatilization studies showed that maximum loss occurred when surface temperature and solar radiation were highest, and that volatile losses were directly related to the vapor pressure characteris tics of the pesticide.

Thus, examining the physical and chemical properties of the pesticide is a good way to determine if volatilization losses are likely to occur under particular weather and application conditions. Haith et al. (2000) found three indices (i.e., Henry's Constant, vapor pressure, and wind speed) explained 70 to 90 percent of the variation in measured volatilization for eight pesticides applied to turf.

Post-application irrigation has an effect on the volatilization of trichlorfon (Murphy et al., 1996a). The pesticide was applied once, followed by 13 mm of irrigation, and again separately with no post-application irrigation. The application rate for both occasions was 9 kg a.i. ha^{-1}. Without post-application irrigation, trichlorfon volatile loss totaled 13 percent compared to 9 percent when irrigated. Also, withholding post-application irrigation resulted in less conversion of trichlorfon to its more toxic breakdown product, DDVP (Figure 1). It appears that light post-application irrigation may have a small, positive effect on preventing volatile loss of pesticides. However, more research investigating light irrigation on several pesticides is needed to confirm this observed trend.

Water Solubility

The extent to which a chemical will dissolve in a liquid is referred to as solubility. Although water solubility is usually a good indicator of mobility (Figure 2), it is not necessarily the only criterion. In addition to pesticide solubility, the affinity of a pesticide to adhere to soils must be considered (Smith and Bridges, 1998).

Sorption

The tendency of a pesticide to leach or runoff is strongly dependent upon the interaction of the pesticide with solids in the soil. Sorption includes the process of adsorption and absorption. Adsorption refers to the binding of a pesticide to the soil particle surface. Absorption implies that the pesticide penetrates into a soil particle or is taken up by plant leaves or roots. This difference is important because pesticides may become increasingly absorbed with time (months to years), and desorption (or release) of the absorbed pesticide may be reduced with time. The unavailable or undetachable pesticide is often referred to as bound residue and is generally unavailable for microbial degradation or pest

	Weekly Irrigation Regime[1]	
Sample	One 25-mm	Four 6-mm
	----- % of Total Applied -----	
Volatilization	0.9	2.3
Clippings, Verdure	14.3	37.3
Thatch-Mat	11.3	16.7
0-10 cm	13.4	12.6
10-20 cm	7.7	6.4
20-30 cm	7.2	5.6
30-40 cm	7.8	6.7
40-50 cm	7.6	2.2
Leachate**	12.3	0.4
Total	82.4	89.7

[1] Each treatment had six replications.

** Significantly different (t-test, $P < 0.001$)

Adapted from Starrett et al. (1995).

Table 1. Percentage of nitrogen recovered from intact soil cores for two irrigation treatments

Pesticide	Volatile Residues % applied	Comments	Reference
Trichlorfon	11.6	Applied 9/28/91 on bentgrass fairway, no irrigation following application. Sampled for 15 days.	Murphy et al. (1996a)
	9.4	Applied 7/7/93 on bentgrass fairway, 1.3 cm of irrigation after application. Sampled for 15 days.	Murphy et al. (1996a)
	0.09	Applied 6/4/96 on bentgrass green. Sampled for 29 days.	Yates et al. 1996
Isazofos	11.4	Applied 8/22/93 on bentgrass fairway, 1.3 cm of irrigation after application. Sampled for 15 days.	Murphy et al. (1996a)
	1.04	Applied 10/4/96 on bermudagrass green, 0.6 cm of irrigation followed by 3.94 cm of rainfall over 24 hrs. Sampled 48 hours during cloudy, rainy conditions.	Snyder and Cisar (1996)
	9.14	Applied 10/10/96 on bermudagrass green, 0.6 cm of irrigation after application. Sampled 22 hrs, no rainfall.	Snyder and Cisar (1996)
Chlorpyrifos	2.7	Applied 10/4/96 on bermudagrass green, 0.6 cm of irrigation followed by 3.94 cm of rainfall over 24 hrs. Sampled 48 hours during cloudy, rainy conditions.	Snyder and Cisar (1996)
	11.6	Applied 10/10/96 on bermudagrass green, 0.6 cm of irrigation after application. Sampled 22 hrs, no rainfall.	Snyder and Cisar (1996)
	15.7	Applied 6/4/96 on bentgrass green. Sampled 29 days.	Yates et al. 1996
Fenamiphos	0.04	Applied 10/10/96 on bermudagrass green, 0.6 cm of irrigation after application. Sampled 22 hrs, no rainfall.	Snyder and Cisar (1996)
	0.25	Applied 10/4/96 on bermudagrass green, 0.6 cm of irrigation followed by 3.94 cm of rainfall over 24 hrs. Sampled 48 hours during cloudy, rainy conditions.	Snyder and Cisar (1996)
Carbaryl	0.03	Applied 8/93 to bentgrass green and bermudagrass fairway plots. Value is average over turfgrass and soil types.	Yates et al. 1996
Triadimefon	7.3	Applied 8/23/91 on bentgrass fairway, 1.3 cm of irrigation after application. Sampled 15 days.	Murphy et al. (1996b)
Metalaxyl	0.08	Applied 9/27/96 on bentgrass green. Sampled 8 days.	Yates et al. 1996
Chlorthalonil	0.02	Applied 9/27/96 on bentgrass green. Sampled 8 days.	Yates et al. 1996
Mecoprop	0.08	Applied 9/24/92 on bentgrass fairway, no irrigation following application. Sampled 15 days.	Murphy et al. (1996b)
2,4-D	0.67	Applied 8/93 to bentgrass green and bermudagrass fairway plots. Averaged of turfgrass and soil types.	Yates et al. (1995)

Table 2. Summary of volatile insecticide residues recovered from putting green and fairway plots

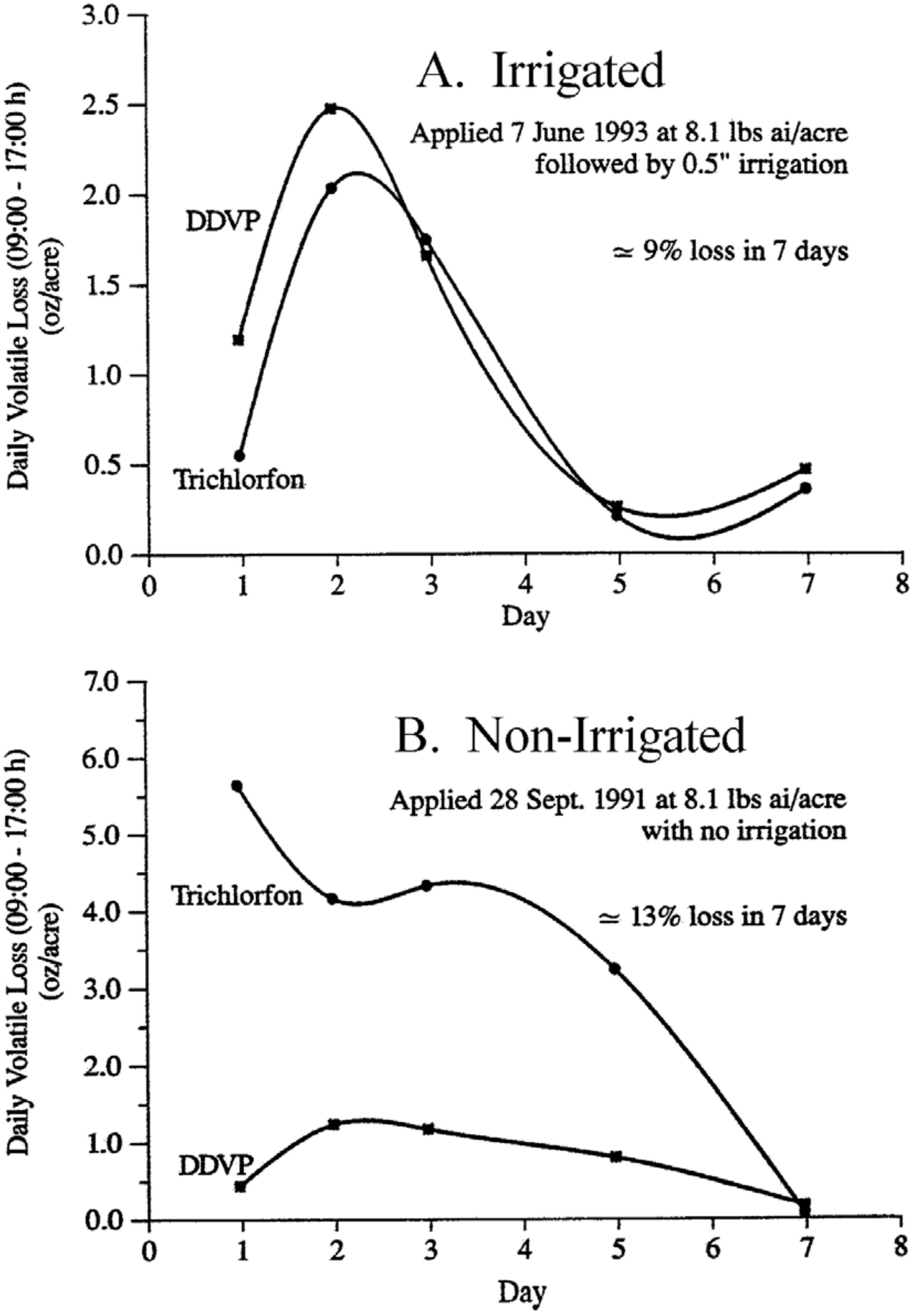

Figure 1. Trichlorfon volatilization from irrigated (A) and non-irrigated (B) bentgrass fairway plots. From Cooper et al. (1995).

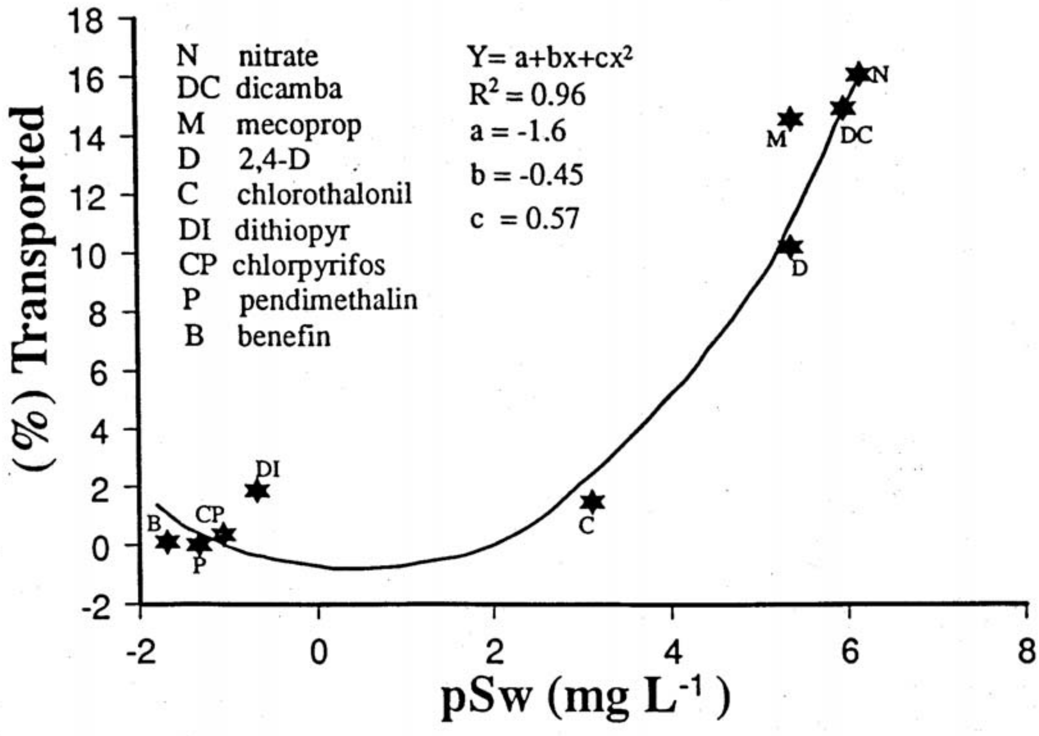

Figure 2. Fraction of the applied pesticides transported from simulated fairway plotted for the log of the water solubility (pSW) of the analyte. From Smith and Bridges (1998).

Rootzone Medium	Nitrogen kg N $ha^{-1}yr^{-1}$	NO_3-N, % of Total N		
		Year 1	Year 2	Year 3
Sand	190	5.37	0.06	2.71
	390	6.31	0.04	3.17
	585	7.55	0.70	4.28
Amended Sand	190	5.37	0.40	0.16
	390	0.91	0.02	0.17
	585	3.37	1.26	2.31

Adapted from Brauen and Stahnke (1995).

Table 3. Percent of total applied nitrogen leached as nitrate from pure sand and amended sand putting greens.

control.

Factors that contribute to sorption of pesticides on soil materials include a) chemical and physical characteristics of the pesticide, b) soil composition, and c) nature of the soil solution. In general, sandy soils offer little in the way of sorptive surfaces. Soils containing higher amounts of silt, clay and organic matter provide a rich sorptive environment for pesticides. Research conducted during the past eight years (Carroll and Hill, 1998; Sigler et al., 2000; Lickfeldt and Branham, 1995) indicates that turfgrass leaves and thatch adsorb a significant amount of pesticide (Figure 3).

Adsorption of pesticides is affected by the partition coefficient, which is reported as Kd or more accurately as Koc. A Koc less than 300 to 500 is considered low. The strength of adsorption is inversely related to the pesticide's solubility in water and directly related to its partition coefficient. For example, chlorinated hydrocarbons are strongly adsorbed, while phenoxy herbicides like 2,4-D are much more weakly adsorbed.

Plant Uptake

Plants can directly absorb pesticides or influence pesticide fate by altering the flow of water in the root zone. Turfgrasses with higher rates of transpiration can reduce the leaching of water-soluble pesticides. In situations where the turf is not actively growing or root systems are not well developed, pesticides are more likely to migrate deeper into the soil profile with percolating water.

Degradation

Degradation occurs because of the presence of soil microorganisms and chemical processes in the turfgrass-soil system. Pesticides are broken down in a series of steps that eventually lead to the production of CO_2 (carbon dioxide), H_2O (water) and some inorganic products (i.e., nitrogen, phosphorus, sulfur, etc.). Sigler et al. (2000) provides an excellent review of pesticide degradation in turfgrass systems.

Microbial degradation is a biological process whereby microorganisms transform the original compound into one or more new compounds. Each of these new compounds has different chemical and physical properties that make them behave differently in the environment. Microbial degradation may be either direct or indirect. Some pesticides are directly utilized as a food source by microorganisms. In most cases, though, indirect microbial degradation of pesticides occurs though passive consumption along with other food sources in the soil.

Chemical degradation is similar to microbial degradation except that pesticide break down is not achieved by microbial activity. The major chemical reactions such as hydrolysis, oxidation, and reduction occur in both chemical and microbial degradation. Photochemical degradation is an entirely different break down process driven by solar radiation. It is the combined pesticide degradation that results from chemical, microbial, and photochemical processes under field conditions that was of the most interest in the USGA sponsored studies.

Degradation rates are also influenced by factors like pesticide concentration, temperature, soil water content, pH, oxygen status, prior pesticide use, soil fertility, and microbial population. These factors change dramatically with soil depth and greatly reduce microbial degradation as pesticides migrate below the soil surface. An interesting result occurred at the University of Florida study when fenamiphos was applied twice at a monthly interval. Although leaching from the first application amounted to about 18 percent, leaching from the second application was just 4 percent (Snyder and Cisar, 1993; Cisar and Snyder, 1993; Cisar and Snyder, 1996). These results suggest that microbial degradation was enhanced due to microbial buildup after the first application, thereby reducing the amount of material available for leaching after the second application.

In the case of degradation rates, the average DT_{90} (days to 90% degradation) in turf soils generally is significantly less than established values based upon agricultural systems (Figure 4). Thus, leaching potential for most pesticides is less in turfgrass systems because turfgrass thatch plays an important role in adsorbing and degrading

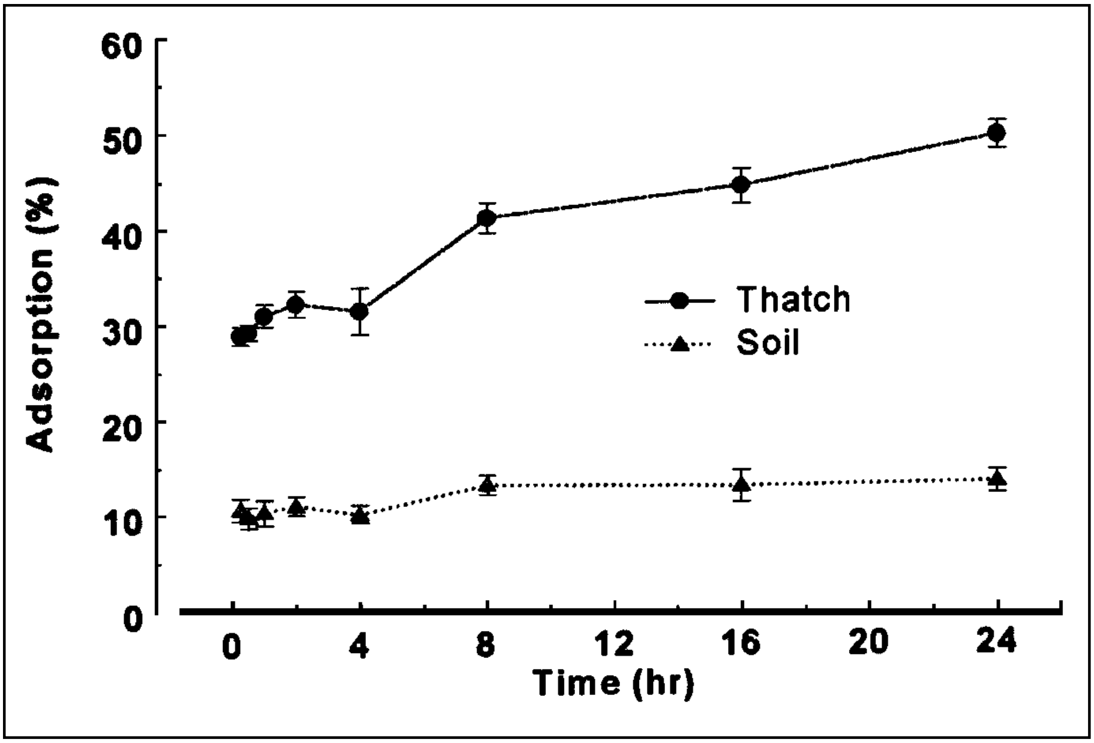

Figure 3. Adsorption kinetics for 2,4-D in thatch and soil. From Carrol and Hill (1998).

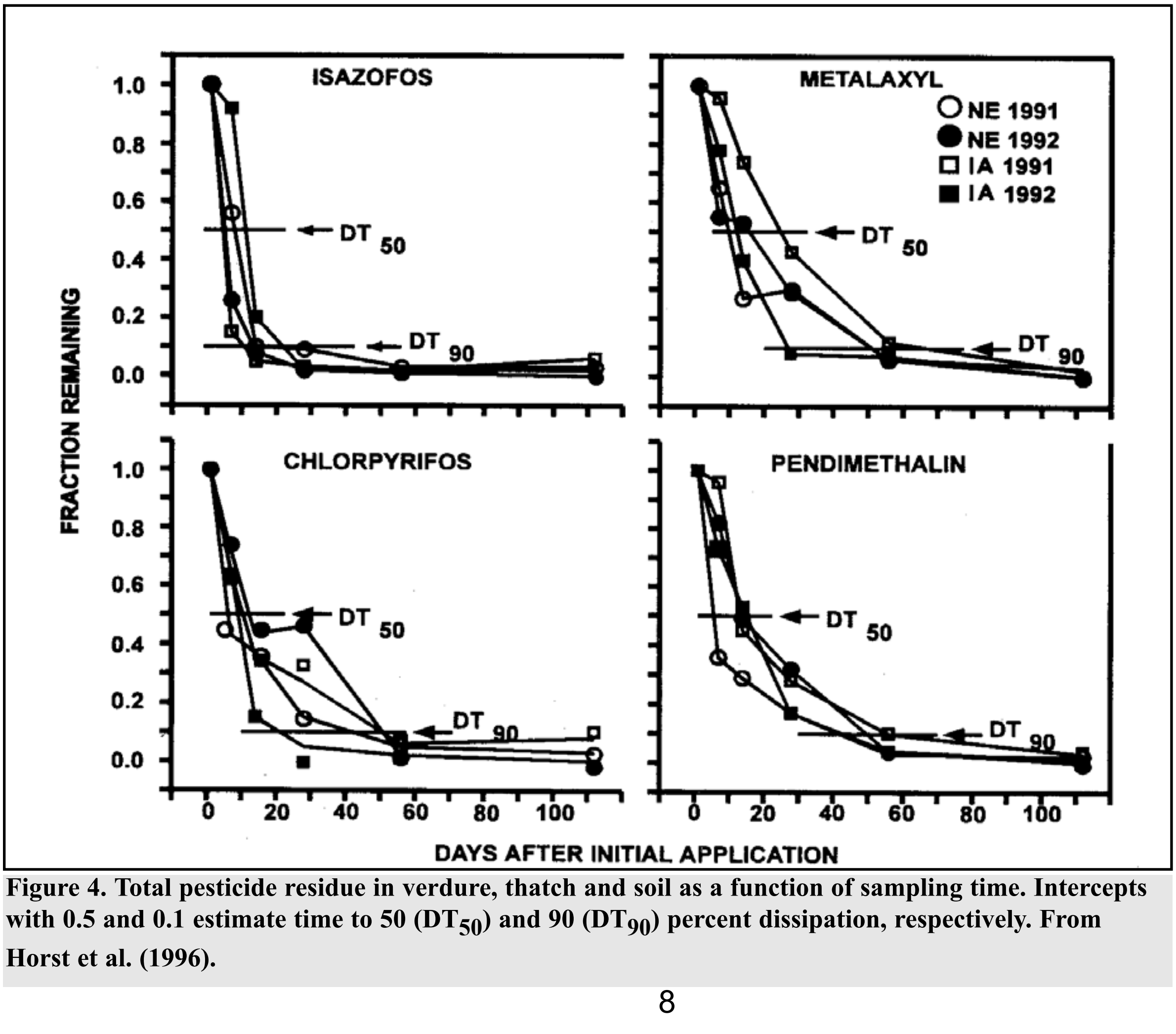

Figure 4. Total pesticide residue in verdure, thatch and soil as a function of sampling time. Intercepts with 0.5 and 0.1 estimate time to 50 (DT_{50}) and 90 (DT_{90}) percent dissipation, respectively. From Horst et al. (1996).

applied pesticides (Horst et al., 1996).

Persistence of a pesticide, expressed as half-life (DT_{50}), is the time required for 50 percent of the original pesticide to degrade. Half-life measurements are commonly made in the laboratory under uniform conditions. On the golf course, soil temperature, organic carbon and moisture content change constantly. These factors dramatically influence the rate of degradation. Consequently, half-life values should be considered as guidelines rather than absolute values.

Leaching

The downward movement of nutrients and pesticides through the turfgrass-soil system by water is called leaching. Compared to some agricultural crops, the USGA-sponsored research demonstrates that leaching is reduced in turfgrass systems. This occurs because of the increase in adsorption on leaves, thatch, and soil organic matter; a high level of microbial and chemical degradation; and reduced percolation due to an extensive root system, greater plant uptake, and high transpiration rates. Separate discussions on nitrogen, phosphorous and pesticide leaching follow.

Golf courses use a significant amount of nitrogen (N) fertilizer and there is concern that nitrogen leaching is affecting groundwater supplies. Seven different universities investigated nitrogen leaching, most using bucket lysimeters to measure leaching potential. In general, very little nitrogen leaching occurred when nitrogen was applied properly i.e., according to the needs of the turf and in consideration of soil types, irrigation regimes and anticipated rainfall. Properly maintained turf grown in a loam soil allowed less than one percent of the nitrogen applied to leach to a depth of 1.2 m (Miltner et al., 1996). Sandy soils are more prone to leaching losses than loam soils.

Results averaged over seven leaching projects during the establishment year indicate that nitrogen leaching ranged from 11 percent of applied for pure sand rootzones to one percent or less for rootzones containing more silt and clay (Figure 5). When more nitrogen is applied than is needed, both the amount and the percentage of nitrogen lost increases. Nitrogen leaching losses can be greatly reduced by irrigating lightly and frequently, rather than heavily and less frequently. Applying nitrogen in smaller amounts on a more frequent basis also reduced leaching losses.

Braun and Stahnke (1995) found that nitrogen leaching was significant when applied at heavy rates to newly established turfgrass on pure sand rootzones. For example, they found that 7.6 percent of an annual application rate of 585 kg N ha^{-1} yr^{-1} (12 lb. N 1000 ft^{-2} yr^{-1}) applied to immature turf grown on a pure sand rootzone leached through the profile (Table 3). Leaching was significantly less when peat was added to the sand (USGA guidelines), occurring at a level of about three percent. On pure sand, nitrogen concentrations exceeded federal drinking water standards (10 ppm NO_3-nitrogen) several times at the 585 kg rate during the first year, whereas nitrogen concentrations in leachate never exceeded federal standards from the sand/peat mix.

Significantly less leaching also occurred when less nitrogen was applied (<380 kg N ha^{-1} yr^{1}) and when application frequency was increased (22 vs. 11 times annually). During years two and three, on mature turf, much less nitrogen leaching occurred for all treatments. In putting green construction, mixing peat moss with sand significantly reduced nitrogen leaching compared to pure sand rootzones during the year of establishment. Light applications of slow-release nitrogen sources on a frequent interval provided excellent protection from nitrate leaching.

Miltner et al. (1996) reported that less than one percent of the applied nitrogen leached through a 1.2-m (4-foot) deep profile of undisturbed loam-soil during a 2.5-year period (Figure 6). Most of the nitrogen was recovered in clippings, thatch, and soil. They suggested that the remaining amount volatilized or was lost through denitrification. Starrett et al. (1995) observed similar results when nitrogen was applied at moderate rates and lightly irrigated (one 25-mm vs. four 6-mm applications). However, up to 30 times more nitrogen (Table 1) was leached after the single 25 mm irrigation application, perhaps in part due to macropore flow caused by earthworm activity. Yates (1995) reported that nitrogen leaching from

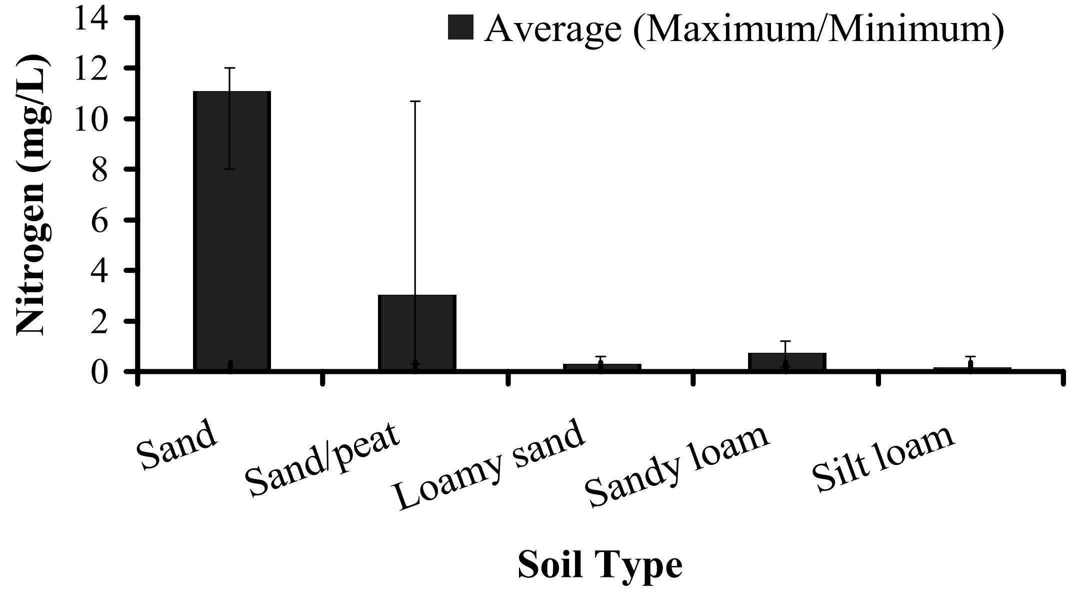

Figure 5. Summary of the nitrogen leaching results (mg L^{-1}) from five soil types reported from USGA-sponsored research studies.

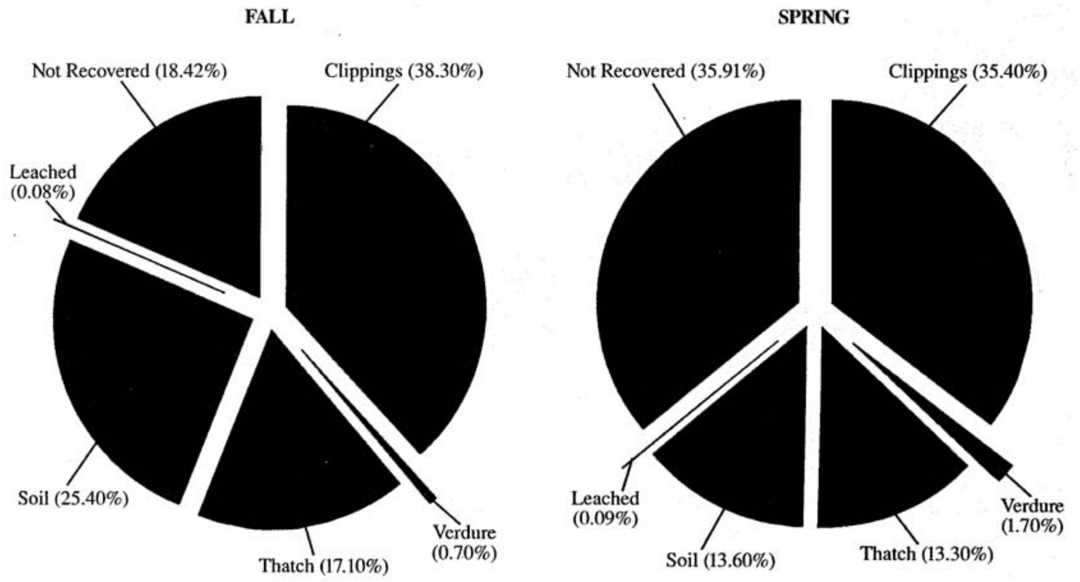

Figure 6. Percent of total nitrogen applied recovered two years after spring and fall applications to a Kentucky bluegrass turf. From Kenna (1994).

a USGA profile sand-based green was generally less than one percent when nitrogen was applied lightly and frequently.

Irrigating bermudagrass and tall fescue turf with adequate amounts (no drought stress) of moderately saline water did not increase the concentration or amount of nitrate leached (Bowman et al., 1995). Higher amounts of salinity in the root-zone, drought, or the combination of these two stresses caused high concentrations and larger amounts of nitrate to leach from both a tall fescue and bermudagrass turf. This suggests that drought, high salinity, or both impair the capacity of the root system of the turf, and that management modification may be needed to prevent nitrate leaching.

Phosphorous (P) has been considered an immobile element in turfgrass and agricultural soils. Branham et al. (2000) reported that soil levels of phosphorous increased rapidly after only one to two years of annual fertilizer applications. Phosphorous applications of 200 kg ha^{-1} to a P-deficient turf growing on a sandy soil increased soil P test values in the 0-7.5 cm soil layer from 3 mg kg^{-1} to 9.6 mg kg^{-1}. Soil P rose to 25.3 mg kg^{1} the following year after applying only 50 kg P ha^{1} during the growing season. Actual phosphorous leaching was not measured in these experiments.

Shuman et al. (2000) reported that phosphorous was found in leachate collected from putting greens on a golf course in Atlanta, Georgia. Lysimeters were installed and the putting greens were seeded to bentgrass in September 1994, so the years recorded include the establishment period. During the first year, the phosphorous concentration was over 3 mg L^{-1}, which is high enough to cause algae growth. They assumed the phosphorous may have come from a an 1994 application at establishment since very little was added in 1995 (25 mg ha^{-1}). Phosphorous added to the new green may have been more susceptible to leaching because of reduced uptake by young turf.

Pesticide leaching studies were conducted at universities throughout the United States. Treatments were made to a variety of soils and turf species, and plots received varying irrigation regimes or rainfall events. During the first year of the studies, most turf areas were relatively immature. Results showed that very little pesticide leaching occurred with most products, generally less than one percent of the total applied. However, significant leaching occurred with certain products and under certain circumstances (Table 4).

The physical and chemical properties of the pesticides proved to be good indicators of the potential for leaching, runoff and volatilization (Kenna, 1994 and Sigler et al., 2000). Products that exhibit high water solubility, low soil adsorption potential, and greater persistence are more likely to leach and run off. For example, fenamiphos, a commonly used nematicide, is highly water soluble, has low adsorption potential, and its toxic breakdown metabolite tends to persist in the soil. Actual losses of fenamiphos and its metabolite due to leaching were as high as 18 percent from a sand-based green in Florida (Snyder and Cisar, 1993; Cisar and Snyder, 1993; Cisar and Snyder, 1996), though when all studies are considered, the average loss was about five percent.

Soil type and precipitation/irrigation amount also were important factors in leaching losses. Table 5 shows the effects of soil type and precipitation on leaching of MCPP and triadimefon, two pesticides whose chemical and physical properties indicate a relatively high potential for leaching. Results show significant leaching from coarse sand profiles, especially under high precipitation, and much less leaching from sandy loam and silt loam soils (Petrovic, 1995).

There are several simulation models currently used to predict the downward movement of pesticides through soil. A good review on pesticide transport models was conducted by Cohen et al. (1995). The USGA-sponsored studies indicate that many of these models will need adjustments that take into account the role of a dense turf canopy and thatch layer. For example, when the canopy and thatch layer are ignored, the predicted value using the GLEAMS (i.e., Groundwater Loading Effects of Agricultural Management Systems) computer model was much higher than

Common Name	Trade Name	n	Total Recovered Mean	(Range)	Percent Recovered Mean	(Range)
			-------- micro g m^{-2} --------		---------- % ----------	
Fairway Plots						
Chlorothalonil	Daconil	1	0	(0)	0.00	(0.00)
Fenarimol	Rubigan	1	0	(0)	0.00	(0.00)
Metalaxyl	Subdue	1	0	(0)	0.00	(0.00)
Propiconazole	Banner	1	0	(0)	0.00	(0.00)
Triadimefon	Bayleton	8	2,312	(27-11,160)	0.51	(0.01-2.44)
2,4-D	2,4-D	9	155	(0- 329)	0.28	(0.00-0.60)
Dicamba	Banvel	2	4,750	(3,700-5,800)	39.58	(30.83-48.33)
MCPP	Mecoprop	6	44,236	(1,006-142,062)	19.34	(0.44-62.12)
Carbaryl	Sevin	8	132	(24-375)	0.01	(0.00-0.02)
Isazofos	Triumph	6	5,590	(5,590)	2.44	(0.00-10.40)
Trichlorfon	Proxol	6	21,527	(5,763-40,341)	2.35	(0.63-4.41)
Putting Green Plots						
Chlorothalonil	Daconil	4	2,961	(749-5,486)	0.08	(0.02-0.14)
2,4-D	2,4-D	7	871	(347-1,808)	2.25	(1.12-3.79)
2,4-D amine	2,4-D	6	46	(0-133)	0.12	(0.00-0.48)
Dicamba	Banvel	7	201	(0-1,173)	3.07	(0.00-19.55)
MCPP	Mecoprop	4	109	(0-329)	0.08	(0.00-0.25)
Carbaryl	Sevin	4	372	(205-642)	0.04	(0.02-0.07)
Chlorpyrifos	Dursban	4	92	(0-193)	0.04	(0.00-0.08)
Dithiopyr	Dimension	4	139	(101-196)	0.24	(0.18-0.35)
Ethoprop	Mocap	1	41,138	(1,138)	0.05	(0.05)
Fenamiphos	Nemacur	4	53,121	(419-199,038)	4.70	(0.04-17.61)
Fonofos	Dyfonate	2	54	(4-103)	0.01	(0.00-0.02)
Isazofos	Triumph	2	123	(41-204)	0.05	(0.02-0.09)
Isofenphos	Oftanol	2	43	(33-53)	0.02	(0.01-0.02)

Table 4. Summary of total pesticide mass and percent of total applied recovered in water effluent from putting green and fairway lysimeters.

Pesticide	Precipitation	Sand	Sandy Loam	Silt Loam
		--- % Recovered of Total Applied ---		
MCPP	Moderate	51.0	0.8	0.4
	High	62.1	0.5	1.2
Triadimefon	Moderate	1.0	0.06	0.2
	High	2.4	0.01	0.3

From Petrovic (1995).

Table 5. . Effect of soil type and precipitation on the leaching loss of two pesticides from an immature turf, expressed as percent of total applied.

the actual leaching loss of 2,4-D. Without proper parameter adjustments, the model over-predicted the actual amount leached by 10 to 100 times, or more, for five of the seven pesticides screened by the computer (Smith and Tilloston, 1993; Smith, 1995).

Durborow et al. (2000) evaluated the U.S. EPA's PRZM 3.0 model using data from a USGA-sponsored study in Georgia and Nebraska. The predictions of percolate volumes ranged from poor to good for the Georgia study (CV = 59%) and excellent for the Nebraska study (CV = 18% with no calibration). Predictions of pesticides leachate ranged from poor to good, but PRZM tended to over predict pesticide mass.

In summary, the pesticide leaching studies indicate that dense turf cover and thatch layer reduced the potential for leaching losses of pesticides; conversely, more leaching occurred from newly planted turf stands. Generally, sandy soils are more prone to leaching losses than clay soils. The physical and chemical properties of the pesticides were good indicators of leaching potential. However, the current pesticide models tend to over-predict the leaching loss of most pesticides applied to turf if valid adjustments are not made to account for the role the turf canopy and thatch.

Runoff

An important finding from the USGA-sponsored research was that pesticide and nutrient runoff pose a greater threat to water quality than leaching. Runoff refers to the portion of precipitation (rainfall) that is discharged from the area through stream channels. The water lost without entering the soil is called surface runoff, and that which enters the soil before reaching the stream is called groundwater runoff or seepage flow from ground water. Pesticides and nutrients applied to golf course turf, under some circumstances, can be transported off site in surface runoff.

Three USGA-sponsored studies examined runoff from fairway research plots. In Pennsylvania, runoff experiments were conducted on plots characterized by slopes of 9 to 13 percent, good quality loam soil, and turf cover consisting of either creeping bentgrass or perennial ryegrass cut at a 12.5 mm (1/2-inch) fairway height (Linde, 1993; Linde et al., 1995; Linde et al., 1995). Typical of that part of the country, the fairway-type plots received 195 kg N ha^{-1} yr^{-1}. The irrigation water used to simulate rainfall contained a relatively high level of nitrate-nitrogen, ranging from 2 to 10 ppm. They reported that nitrate concentrations in the runoff or leaching samples did not differ significantly from the nitrate concentration in the irrigation water (Figure 7). The study was conducted on excellent quality turf and on soil with a high infiltration rate.

Nitrogen runoff also was measured as part of the studies in Georgia (Smith and Bridges, 1996; Smith and Bridges, 1997). Nitrogen applications were made and 24 hours after a simulated storm event (25 mm applied at a rate of 50 mm hr^{1}) as much as 40 to 70 percent of the rainfall left the plots as runoff. A total of 16 percent (12.5 mg L^{-1}) of the nitrate nitrogen applied at 24 kg ha^{-1} applied to actively growing bermudagrass was found in surface runoff water (Table 6). However, 64 percent (24.8 mg L^{-1}) of the nitrate nitrogen applied at 24 kg ha^{-1} applied to dormant bermudagrass was found in surface runoff water.

In Oklahoma, the effects of buffer strips and cultivation practices on pesticide and nitrogen runoff were investigated. It was concluded that antecedent soil moisture was the major factor influencing runoff (Table 7). During the first simulated rainfall event in July, soil moisture conditions were low to moderate. After a 50 mm (2 inches) rainfall event, less than one percent of the applied nitrogen was collected in the runoff (Baird, 1996; Cole et al., 1997). In August, when the simulated rainfall occurred after 150 mm (6 inches) of actual rainfall the previous week (i.e., high soil moisture), the amount of nitrogen collected after the simulated rainfall averaged more than 8 percent. When soil moisture was moderate to low in the Oklahoma study, the presence of a 2.4 to 4.9 m (8 to 16 ft.) untreated buffer strip significantly reduced nitrogen runoff, whereas when soil moisture was high, the buffer strips made no difference. In both cases, less runoff occurred when sulfur-coated urea was applied compared to straight urea.

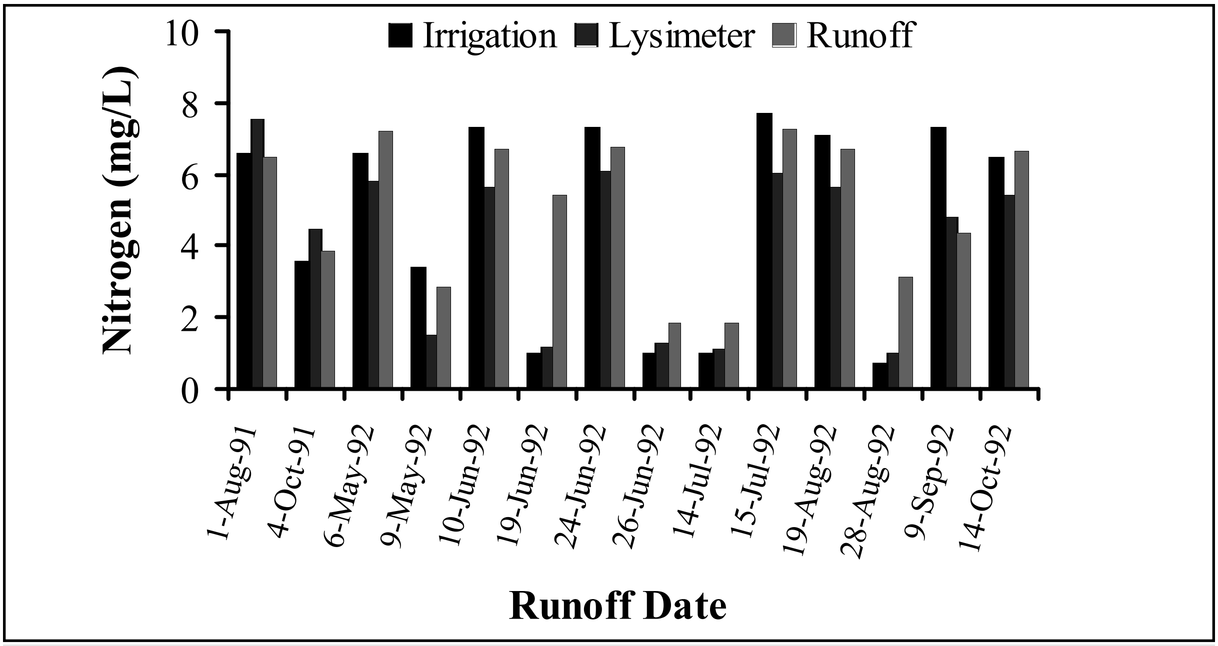

Figure 7. Concentration of nitrate-nitrogen in irrigation, leachate, and runoff water collected during the 1993 growing season. From Linde (1993).

Pesticide or Nitrogen Treatment	Application Rate	Percentage Transported	Concentration 24 hours after Application
	-- kg ha^{-1}--	---- % -----	----- micro grams L^{-1} -----
NO_3 active growth	24.4	16.4	12,500
NO_3 dormant	24.4	64.2	24,812
Dicamba	0.56	14.6	360
Dicamba (dormant)	0.56	37.3	752
Mecoprop	1.68	14.4	810
Mecoprop (dormant)	1.68	23.5	1,369
2,4-D DMA	2.24	9.6	800
2,4-D DMA (dormant)	2.24	26.0	1,959
2,4-D DMA (injected)	2.24	1.3	158
2,4-D DMA (buffer)	2.24	7.6	495
2,4-D LVE	2.24	9.1	812
Trichlorfon1	9.15	32.5	13,960
Trichorfon 1(injected)	9.15	6.2	2,660
Chlorothalonil[2]	9.50	0.8	290
Chlorpyrifos[2]	1.12	0.1	19
Dithiopyr	0.56	2.3	39
Dithiopyr (granule)	0.56	1.0	26
Benefin	1.70	0.01	3
Benefin (granule)	1.70	0.01	6
Pendimethalin	1.70	0.01	9
Pendimethalin (granule)	1.70	0.01	2

[1] Trichlorfon + dichlorvos metabolite.

[2] Total for active ingredient and metabolites.

From Smith and Bridges (1997).

Table 6. The percentage of applied and concentration of product transported from runoff plots during rainfall 24 hours after application on heavy textured soils with high antecedent moisture.

In summary, results from USGA-sponsored runoff studies showed that dense turf cover reduces the potential for runoff losses of nitrogen, and significant runoff losses are more likely to occur on compacted soils. Much greater nitrogen runoff occurred when soil moisture levels were high, as compared to moderate or low. Buffer strips reduced nitrogen runoff when soil moisture was low to moderate at the time of the runoff event. However, buffer strips were ineffective when soil moisture levels were high. Nitrogen runoff was significantly less when a slow release product (sulfur-coated urea) was used compared to a more soluble product (urea).

Watschke et al. (2000) reported that MCPP, triadimefon and isazofos were found in the first and second liters of runoff water collected 24 hours after application (Table 8). Runoff was forced with a very high irrigation rate (152 mm hr^1) which far exceeds any rate being used on golf courses. Two months after application, no residues could be detected for any of the three pesticides. Treatments were applied to large perennial ryegrass and creeping bentgrass plots maintained as golf course fairways. Slightly more pesticide residue was collected for perennial ryegrass fairways than for bentgrass. Collected residues decreased from the first year (1992) to the second year (1993) as both turfgrass species matured.

In Georgia, studies were conducted on plots with a 5 percent slope and a sandy clay soil typical of that region (Smith and Bridges, 1998; Smith and Tiloston, 1993; Smith, 1995; Smith and Bridges, 1996). Pesticides were applied and 25-mm (1-inch) simulated rainfall events occurred 24 and 48 hours afterward. At a rainfall rate of 50 mm (2 inches) per hour, as much as 40 to 70 percent of the rainfall left the plots as runoff during simulated storm events.

The collected surface water contained moderately high concentrations of treatment pesticides having high water solubility (Table 6). For example, under these conditions, only very small amounts (<1%) of chlorthalonil and chlorpyrifos could be detected in the runoff. However, between 10 to 13 percent of the 2,4-D, MCPP and dicamba was transported off the plots over an 11-day period. About 80 percent of this transported total moved off the plots with the first rainfall event 24 hours after pesticide application. Also, the amount of the trichlorfon that ran off the plots was 5.2 times greater when broadcast as a granular product compared to being pressure injected. Finally, the runoff loss of several herbicides was greater when applied to dormant turf as compared to an actively growing turf.

Antecedent soil moisture was a significant factor in determining how much pesticide ran off the plot areas (Smith and Bridges, 1996; Baird, 1996; Baird, 1998). Where soil moisture was low to moderate, buffer zones were effective in reducing pesticide runoff; when soil moisture was high they were not effective except for the insecticide chlorpyrifos (Table 7).

In both Oklahoma and Georgia, best management practice studies investigated how cutting heights and buffers of varying lengths could minimize fertilizer and pesticide runoff. The effect of soil cultivation (core aerification) on runoff potential also was studied. In Oklahoma, a 4.9-m buffer cut at 5 cm (3 inches) significantly decreased the amount of 2,4-D found in runoff water from a 4.9-m treated bermudagrass fairway (Figure 8). However, the results in Georgia that used smaller buffer strips indicated no reduction in the amount of pesticide transported in the surface-water solution (Baird, 1998).

Among the conclusions or trends observed from the pesticide runoff studies were the following: 1) dense turf cover reduces the potential for runoff losses of pesticides; 2) turfgrass species can affect runoff, 3) the physical and chemical properties of pesticides are good indicators of potential runoff losses; 4) heavy textured, compacted soils are much more prone to runoff losses than sandy soils; 5) moist soils are more prone to runoff losses than drier soils; 6) buffer strips at higher cutting heights tend to reduce runoff of pesticides when soil moisture is low to moderate prior to rainfall events; and, 7) the application of soluble herbicides on dormant turf can produce high levels of runoff losses.

Human Exposure to Pesticides

Soil Moisture	NO_3	PO_4	NH^4	Dicamba	2,4-D	MCPP	Chlorpyrifos	ref.
Low/mod.	0.09	0.2	0.2	0.35	0.79	0.81	0.04	(38)
	-	-	-	3.1	2.6	1.3		(36)
High	3.1	7.7	5.1	5.4	8.7	9.3	0.025	(38)
	-	-	-	9.7	7.3	9.5		(36)

Adapted from Smith and Bridges (1997) and Cole et al. (1997).

Table 7. Effect of low/moderate versus high antecedent soil moisture levels on pesticide and nutrient runoff losses from bermudagrass maintained as fairway turf, expressed as a percent of total applied.

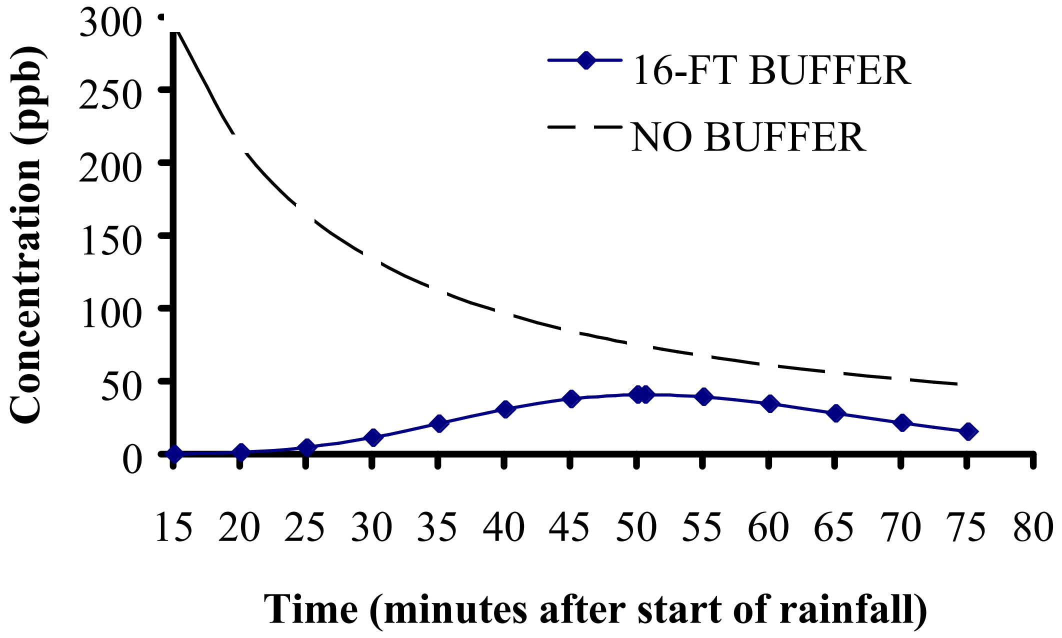

Figure 8. Plot of the predicted concentration of 2,4-D in surface runoff versus time in 1996 buffer length experiment on bermudagrass fairways. From Baird (1998).

People are concerned about exposure they receive during a round of golf on turf that has been treated with pesticides. Exposure in this situation is caused by pesticide residues on the turf surface that rub off onto people or their equipment during a round of golf. A preliminary risk assessment was conducted for golfers who are exposed to a putting green treated with insecticides. Under the assumptions of this study, the golfer would have received about 1/3 of the lifetime reference dose considered safe by the US EPA (Borgert et al., 1994). This is not to say that golfers or workers could not receive unsafe exposure to pesticides on golf courses. Under the conditions of this study, though, the golfer would not have been at significant risk.

Other studies that have determined dislodgeable residue levels indicate that less than one percent of the pesticides could be rubbed off immediately after application when the turf was still wet. In addition, the one percent could be reduced significantly by irrigating after the pesticide was applied. After the pesticides dried on the turf, only minimal amounts could be rubbed off.

Volatilization studies report that organophosphate insecticides that possess high toxicity and volatility might result in exposure situations that cannot be deemed completely safe as judged by the US EPA Hazard Quotient determination (Table 9). Additional biomonitoring studies will be needed to determine the extent of the risk, if any (Cooper et al., 1995; Murphy et al., 1996; l Murphy et al.,1996, Clark, 1997).

Wildlife Links Program

Golf courses offer excellent opportunities to provide important wildlife habitat in urban areas. With more than 17,000 golf course in the United States comprising in excess of 1.5 million acres, great potential exists for golf courses to become an important part of the conservation landscape.

Wildlife Links is a cooperative program with the National Fish and Wildlife Foundation that funds innovative research, management, and education projects that will help golf courses become an important part of the conservation landscape. The United States Golf Association is providing $200,000 annually to fund the grants through the Wildlife Links program.

Since the program began in 1996, ten projects committing over $500,000, were funded to enhance wildlife conservation on golf courses. The objectives of Wildlife Links are to 1) facilitate research on wildlife issues of importance to the golf industry; 2) provide scientifically-credible information on wildlife management to the golf industry; 3) develop wildlife conservation education materials for the golf industry and golfers; and 4) implement wildlife monitoring programs that will improve management on golf courses.

The Wildlife Links Advisory Committee is responsible for the selection and monitoring of grants funded under the Wildlife Links Program. Committee members are experts in fields of wildlife biology and management, pesticide management, habitat management and conservation, education, and the game of golf.

Summary of Past Environmental Research

The university research investigating pesticide and nutrient fate was the first extensive self-examination of golf's impact on the environment. What has the environmental research program told us? The research shows that under most conditions, the small amounts of pesticides and nutrients that move through the soil are found at levels below the health and safety standards established by the U.S. Environmental Protection Agency. These words have been selected very cafully:

- *Most conditions* - There are some conditions where we have some problems.
- *Small amounts of pesticides and nutrients* - its not zero!
- *Move* - Yes, they do move sometimes; however, at levels below health standards

The studies demonstrate that the turfgrass canopy, thatch, and root system, when properly managed, are an effective filter or sponge. Most of the pesticides applied to turfgrass stays in the leaves, thatch or top ten centimeters of soil if there

Pesticide	Year	Turfgrass	24 hrs	1 month	2 months
MCPP					
	1992	Ryegrass	4101[2]	-	0
		Bentgrass	1128	-	0
	1993	Ryegrass	142	0	0
		Bentgrass	168	0	0
Triadimefon					
	1992	Ryegrass	922	32	0.8
		Bentgrass	395	75	0
	1993	Ryegrass	14	1.1	0
		Bentgrass	8.4	1.2	0
Isazofos					
	1993	Ryegrass	678	0	0
		Bentgrass	507	0	0

[1] Adapted from Watschke et al. (2000). Only some of the results are presented in this abbreviated table.

[2] Amount of pesticide residue ($\mu g\ L^{-1}$) found in the first liter of runoff.

Table 8. Residues of three pesticides ($\mu g\ L^{-1}$) collected in runoff water from sloped perennial ryegrass and creeping bentgrass fairway plots.[1]

Group	Pesticide	Day 1	Day 2	Day 3
		---------------- HQ[2]	----------------	----------------
Group 1: high vapor pressure	DDVP	0.06	0.04	0.02
(> 1.0 x 10^{-5} mm Hg)	Ethoprop	50.0	26	1.2
	Diazinon	3.3	2.4	1.2
	Isazofos	8.6	6.7	3.4
	Chlorpyrifos	0.09	0.1	0.04
Group 2: intermediate vapor pressure	Trichlorfon	0.02	0.004	0.004
(10^{-5} mm - 10^{-7} mm Hg)	Bendiocarb	0.02	0.002	0.002
	Isofenphos	n/d[3]	0.02	n/d
	Chlorthalonil	0.001	0.001	0.0003
	Propiconazole	n/d	n/d	n/d
	Carbaryl	0.0005	0.0001	0.00004
Group 3: low vapor pressure	thiophanate-methyl	n/d	n/d	n/d
(< 10^{-7} mm Hg)	Iprodione	n/d	n/d	n/d
	Cyfluthrin	n/d	n/d	n/d

[1] Adapted from Clark (1997).

[2] The HQs reported are the maximum daily IHQ's measured, all of which occurred during the 11:00 a.m. to 3:00 p.m. sampling period.

[3] n/d = non-detect

Table 9. Inhalation hazard quotients (IHQs) for turfgrass pesticides in the high, intermediate and low vapor pressure group[1].

are small amounts of silt or clay present. These results are expected because pesticides tend to interact with the thatch and soil. Therefore, the pesticide solubility and the pesticides affinity to adhere to soils or sorption must be considered together.

An interesting result from USGA-sponsored research is how well thatch adsorbs pesticides. Even for a soluble product such as 2,4-D, the amount of this herbicide adsorbed to thatch was 20 to 30 percent higher than for soil. The decomposing organic matter that turfgrasses produce in the thatch layer has proven to be an excellent filter for pesticides.

As one would expect, the results from all of the USGA-sponsored studies documented that heavy textured soils adsorbed pesticides and fertilizers better than light textured or sandy soils. First, clay or silt particles are much smaller than fine or coarse sand. This impacts the amount of surface area able to bind or adsorb pesticides and nutrients and influences the soil porosity. Second, the chemical properties, or cation exchange capacity, of clay and silt provide more binding sites for nutrients and pesticides. Last, the physical properties of heavy textured soils, particularly the porosity, slow the downward movement of water.

Soil particle size, cation exchange capacity, and porosity are key components in determining whether pesticides and nutrients will leach or runoff from turfgrass systems. However, it is important to note that leaching can occur in the case of newly established turfgrass planted on light textured soils, particularly coarse sands with little organic matter. Turfgrass establishment in a wide range of soils also confirmed that the light textured sands are more prone to nitrogen leaching than amended sand or soils containing more silt or clay.

Another, more important, message from the research was that pesticide and nutrient runoff were more of a threat to water quality than leaching. The research data also indicate that we needed to improve the prediction models applied to turfgrass systems. During the last three years, the research program has made an effort to obtain more information on pesticide and nutrient runoff from heavy textured soils. The USGA also has supported early efforts to use previous research results to fine tune pesticide fate models so they do a better job predicting the impact of golf course turf on water quality.

Future Directions

The pesticide and nutrient fate research program has had a positive impact on golf. The program was run in an unbiased fashion, results have been published in peer-reviewed scientific journals, and the message, be careful and responsible, is getting out to golf course superintendents around the country. It is time to move the direction of environmental research from university plot studies to full scale monitoring of individual golf courses and the watersheds in which they reside.

The two key areas will be the development and evaluation of acceptable best management practices (BMPs) and the incorporation of wildlife habitat management techniques to protect a wide range of animal and plant species that can utilize golf courses. Golf has an opportunity to lead the development of sustainable land use principles that guarantee excellent water quality and natural environments for enjoyment within urban or urbanizing areas. The new projects will strengthen the position that properly constructed and maintained golf courses have very little impact on water quality.

Best Management Practices

Our industry needs to increase the effort to educate turfgrass managers about best management practices (BMPs). This is an effective, practical means of preventing or reducing non-point sources of pollution to a level compatible with water quality goals. The BMPs should encompass design, engineering, construction and managment principles.

Runoff can carry sediments or dissolved chemicals into surface waters. Leaching could move nutrients away from turf roots or pesticides into the groundwater. These are addressed through the use of BMPs to prevent problems from occurring, have safe-guards in place to control any problems; and have a monitoring program to ensure BMPs are working by evaluating environmental quality. Livingston and McCarron (1991) suggest that a stormwater management system might be considered as a "Best Management Practices (BMPs) Train" in which the individual BMPs are considered the cars (Figure 9). The more BMPs incorporated into the system the better the performance of the treatment train.

Land-use BMPs include implementing design, engineering and construction principles, which influence all of these areas (Peacock et al., 1996). Vegetative filters act as natural filters to reduce storm water flow and pollutant load. Turf areas use the natural processes of infiltration, filtration and biological uptake to reduce flows and pollutant loading.Vegetated filters remove sediment and attached chemicals, organic material, trace metals, nutrents (nitrogen and phosphorus).

The length (width) of the vegetated filter strip is an important variable influencing effectiveness because contact time between runoff and vegetation in the filter strip increases with increasing filter strip length. Some sources suggest a minimum of 50 feet of vegetative buffer for maximum effectiveness, and other studies have shown that 15 to 25 feet of turf is an effective filter.

Conservation areas or buffers are where it is critical to maintain and/or establish perennial vegetative cover to protect resources. The most sensitive portions of watercourses are the areas immediately adjacent to the water. A constructed aquatic ecosystem with rooted emergent hydrophytes can be designed and managed to treat runoff like that from equipment wash pads.

Best Management Practices include every aspect of turf maintenance. An inseparable part of the BMP approach is the use of integrated pest management (IPM). In one context, IPM is another BMP. IPM is an ecologically based system that uses biological and chemical approaches to control. As with BMPs, IPM strategies are incorporated into every aspect of turf management especially as they relate to environmental impact.

The first and most important IPM strategy is to select improved grasses with specific adaptation to the climate of the region and show a resistance to environmental stress and pest problems. Using certified seed or sod guarantees true-to-type and pest-free turfgrass cultivars. Second, turfgrass managers should follow scientifically-based cultural practices that will maintain the turf in the healthiest condition and reduce its susceptibility and recovery from pest problems.

A monitoring program for nutrients and pesticides will ensure that the BMPs and IPM are working to protect environmental quality. Recent research has shown that golf courses, if managed properly, are not the polluters that people believe. Seventeen monitoring studies from 36 golf courses in the US, with a total of 16,587 data points from pesticide, metabolite, solvent and nitrate analyses of surface water and groundwater were evaluated. Of these, Health Advisory Levels or Maximum Contaminant Levels (HALs/MCLs) were exceeded in only 0.07 percent of the groundwater samples and 0.29 percent of the surface water samples (Cohen et al., 1999).

A monitoring study in Coastal North Carolina found that surface water on three golf courses had pesticide concentrations below the environmental hazard levels. There was no offsite migration of any pesticides for all three golf courses monitored (Ryals et al., 1998). A properly maintained golf course is a valuable asset to existing or developing communities.

The implementation of BMPs will insure that water quality is protected, or in many cases, improved as it passes through the golf course property. There is no longer room in the turfgrass industry for turfgrass managers who ignore the potential negative environmental impacts that can occur when BMPs are not followed. If turfgrass managers fail to recognize the need to implement BMPs on the property they manage and mistakes occur, then there should be no surprise when local, state, or federal regulations are enacted to regulate how we manage turfgrass systems.

Conclusion

Golf courses provide beautiful green areas within our urban and suburban landscapes.

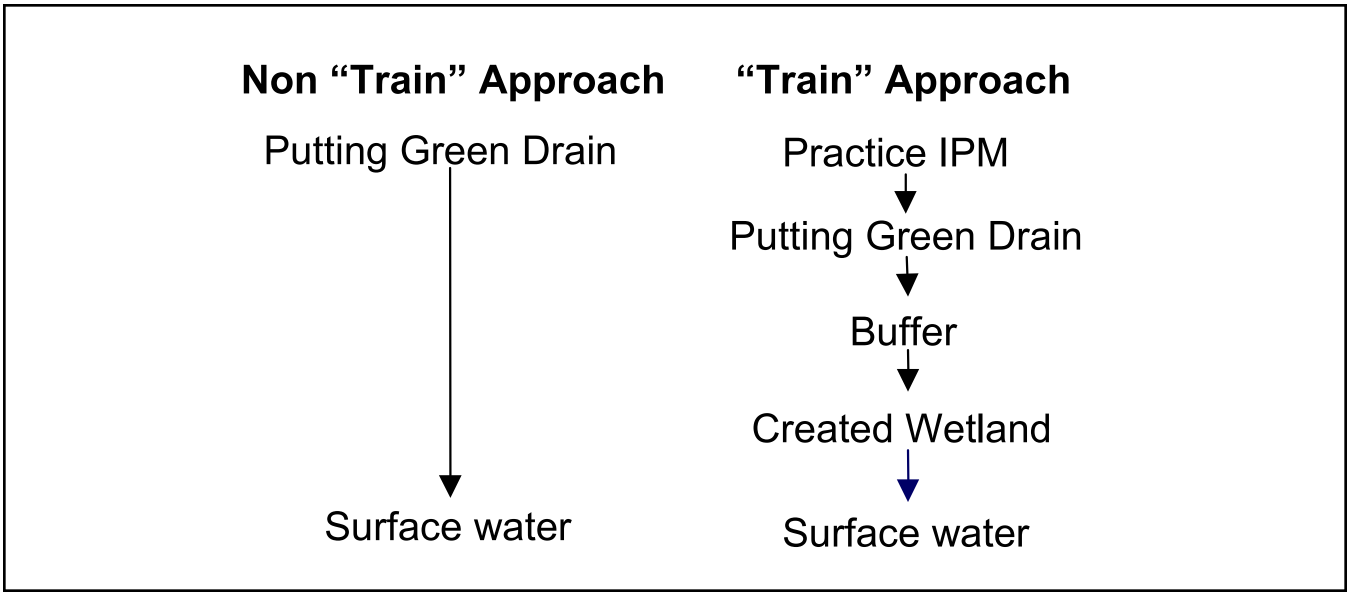

Figure 9. A stormwater management system might be considered as a "Best Management Practices (BMPs) Train" in which the individual BMPs are considered the cars. The more BMPs incorporated into the system the better the performance of the treatment train. Adapted from Livingston and McCarron (1991).

However, there is public concern about the possible effects of golf courses on the environment. Most media attention concerning golf courses tends to focus on the potential negative impacts of turfgrass and golf course management. Although people in our industry know intuitively that there are many benefits associated with turfgrasses and golf courses, the scientific basis for many of these benefits were reported in an exhaustive literature search (Beard and Green, 1994).

In response to public concern, the USGA sponsored university research that examined the degradation and fate of turfgrass chemicals, as well as the development of BMPs and wildlife habitat management methods. The pesticide and nutrient fate research demonstrated that nitrogen and pesticide leaching generally was minimal; the turf/soil ecosystem enhances pesticide degradation; and that the current agricultural models over predict nitrogen and pesticide leaching. Under most conditions, the small amounts of pesticides and nutrients that move through the soil are found at levels below the health and safety standards established by the U.S. Environmental Protection Agency. The important components affecting the fate of pesticides and nutrients are a) the filtering properties of the canopy and thatch; b) soil texture; and c) solubility and adsorption properties of the product applied.

We live in interesting times when the truth and public perception on environmental issues are shaped more by the media and special interest than science and reason. Turfgrass scientists need to look beyond the fairway and understand how the plant species we work with fit in sustainable, urban landscapes. This paper summarizes past environmental research focused on the fate of pesticides and fertilizers applied to turfgrasses; water quality and quantity issues; and efforts to address public concerns about amenity and recreational turfgrass. The paper also looks forward into the future and describes the problems that will face the turfgrass industry and the research needed to address these problems.

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