Ground Water Quality

Bermudagrass Fertilized with Slow-Release Nitrogen Sources. I. Nitrogen Uptake and Potential Leaching Losses

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ABSTRACT

With the objectives of analyzing N recovery and potential N losses in the warm-season hybrid bermudagrass 'Tifgreen' [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy], two greenhouse studies were conducted. Plugs were planted in PVC cylinders filled with a modified sandy growing medium. Urea (URE), sulfur-coated urea (SCU), and Hydroform (HYD) (Hydro Agri San Francisco, Redwood City, CA) were broadcast at rates of 100 and 200 kg N ha^{-1} every 20 and 40 d. The grass was clipped three times every 10 d and analyzed for N concentration and N yield. In addition, leachates were analyzed for NO_3–N. Use of the least soluble source, HYD, resulted in the lowest average clipping N concentration and N yield, as compared with SCU and URE. Clipping N concentration and N yield showed a cyclic pattern through time, particularly under long-day (>12 h) conditions. When the photoperiod decreased below 12 h, leachate NO_3–N concentration exceeded the standard limit for drinking water (10 mg L^{-1}) by 10 to 19 times with the high SCU and URE application rate and frequency. However, leaching N losses represented a minimal fraction (<1%) of the total applied N. More applied N was recovered in plant tissues using SCU and URE (89.5%) than using HYD (64.1%), with more than 52% of applied N accumulating in clippings. Highly insoluble N sources such as HYD decrease N leaching losses but may limit bermudagrass growth and quality. Risks of NO_3–N losses in bermudagrass can be avoided by proper fertilization and irrigation programs, even when a highly soluble N source is used.

During recent years, the effect of agriculture on ground and surface water quality has received considerable attention. Turfgrass cultivation has been identified as a potential NO_3 pollution source of drinking water reserves, especially in urban and suburban areas where golf courses, athletic fields, recreational facilities, and home lawns represent intensive land use areas (Petrovic, 1990). Optimal turf quality (color, density, and texture) requires an intensive N fertilization program, and high N fertilization rates and frequent overwatering have been reported (Exner et al., 1991; Morton et al., 1988). Golf greens, for example, are constructed over a sandy mixture to avoid water flooding, with high infiltration rates (Brown et al., 1982) that accentuate leaching potential.

Turfgrass NO_3 leaching potential is highly variable, owing to its strong dependence on multiple factors, including irrigation practice, soil texture, solubility of N source, N application rates, and the growth rate, stand maturity, and corresponding N demand of the grass (Spalding and Exner, 1993). For example, overwatering with fertilization may generate NO_3–N leaching pollution problems, but proper water management and curtailing of N fertilization during periods of slow growth reduce NO_3–N leaching risk (Liu et al., 1997; Morton et al., 1988; Mosdell and Schmidt, 1985; Rieke and Ellis, 1973; Snyder et al., 1977, 1984). In addition, well-established turfgrass stands have an increased capacity to use soil-applied N compared with newly planted turfgrass (Hesketh et al., 1995). Such capacity has been elaborated in other studies and has been attributed to N immobilization in the thatch layer (Miltner et al., 1996; Nelson et al., 1980), but presumably would also be due to increased N uptake capability as the turfgrass develops greater density following initial establishment.

Use of slow-release N sources will reduce the risk of leaching-induced NO_3–N contamination of drinking water sources, N volatilization, and fertilizer burns, and will allow fewer applications at higher rates (Hummel and Waddington, 1981). In bermudagrass fertilized at 5 g N m^{-2} mo^{-1} with SCU (30% dissolution rate at 7 d), NO_3–N leaching concentration was under the USEPA limit (10 mg L^{-1}), regardless of the irrigation method and frequency (Snyder et al., 1984). However, this study showed that irrigation with a highly soluble N source (NH_4NO_3) produced leachate NO_3–N concentrations three to seven times greater than the USEPA limit during the period 10 to 25 d after treatment. A similar observation comparing isobutylidene diurea (IBDU) and NH_4NO_3 was reported in cool-season grasses such as Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.), and tall fescue (*Festuca arundinacea* Schreb.) (Brown et al., 1982).

The available data on turfgrass N uptake and NO_3 leaching appears to be dominated by work with cool-season turfgrasses. The findings of these studies are difficult to compare because they have been collected under different conditions, such as soil types, grass species and use, water regimes, field and greenhouse environments, and fertilizer N sources (Petrovic, 1990). Moreover, these studies cannot be applied to warm-season grasses in semiarid climates such as New Mexico. Cities in the southwestern U.S. semiarid region are experiencing rapid growth of their urban populations, with ongoing development of golf courses, city parks, home lawns, athletic fields, and other recreational areas. Therefore, more information about fertilizer N fate in

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Abbreviations: HYD, Hydroform; SCU, sulfur-coated urea; URE, urea.

warm-season grasses, such as bermudagrass, is needed (Petrovic, 1990), particularly to study the environmental effect of this intensively managed system on ground water quality.

Our intent was to evaluate the growth, quality, N uptake, and N losses of bermudagrass receiving different sources of N varying in their solubility. In this paper, we discuss the effects of N source, rate, application frequency, and season of year on N recovery, plant N partitioning, and N losses.

MATERIALS AND METHODS

Two experiments were conducted, each 120 d in duration, under greenhouse conditions at the Fabian Garcia Plant Science Center of New Mexico State University, Las Cruces. The 84-m^2 greenhouse was cooled with a conventional pad–fan system and heated with two gas unit heaters.

The first experiment was conducted from 27 Jan. to 29 May 1997. In order to increase photoperiod, artificial light was applied using high-pressure sodium lamps at 1630 to 2000 h to provide a photoperiodic range of 12.93 to 14.97 h (hereafter referred to as long-day conditions). Artificial light intensity ranged from 250 to 300 μmol m^{-2} s^{-1}, and natural light from 550 to 1200 μmol m^{-2} s^{-1} as measured by a quantum sensor (LI-189; LI-COR, Lincoln, NE). Greenhouse temperatures ranged from minima of 12.1 to 22.0°C and maxima of 22.0 to 42.0°C (Table 1). Two gas heaters were used.

The second experiment was conducted from 23 July to 19 Nov. 1997. This experiment was under only natural light conditions and a progressively decreasing photoperiod of 13.92 to 10.62 h (hereafter referred to as decreasing photoperiodic conditions). Temperature ranged from minima of 7.9 to 23.6°C and maxima of 18.2 to 37.4°C (Table 1). A cooling pad–fan system was used. The natural light intensity range was similar to that previously stated.

For both experiments, Tifgreen bermudagrass plugs were washed in tap water to remove all soil, then roots were trimmed to 5 cm in length from the thatch layer. Plugs were placed on the top of the medium (see below) in PVC cylinders (pots) measuring 15.24 cm in diameter and 30 cm in length. Plugs were planted on 12 January for Exp. 1 or 8 July for Exp. 2, irrigated with tap water, and mowed at a height of 1.5 cm every 5 d until the beginning of fertilization treatments (27 January for Exp. 1 and 23 July for Exp. 2). Pot bottoms were covered with plexiglass, and in the center of each cover, a 1-cm-diam. hole was drilled for drainage. The bottom 2.5 cm of each pot was filled with coarse gravel, and the remaining space was filled with growing medium consisting of a 3.8-kg mixture of builder's grade sand and peat moss (93:7 w/w). The Kjeldahl N concentration in peat was 7.8 g kg^{-1} (dry weight) (Bremner, 1996).

Deionized water was used for irrigation. A total of 6.0 and 5.6 L (34.2 and 31.9 cm equivalent depth of water) per pot were applied for Exp. 1 and 2, respectively. The leaching fraction averaged 5.25% for Exp. 1 and 9.05% for Exp. 2. Irrigations were applied every other day. Three N sources were evaluated: (i) URE, 460 g N kg^{-1}; (ii) SCU, 390 g N kg^{-1} and 120 g S kg^{-1} (N dissolution rate of 30–40% at 7 d); and (iii) HYD, 380 g N kg^{-1} (110 g N kg^{-1} as water-soluble N from urea, methylene diurea, and dimethylene triurea, and 270 g N kg^{-1} as water-insoluble N from methylene urea). Fertilizer particle size was standardized, and only those particles that passed through a 10 mesh (2-mm pore size) and held by an 18 mesh (1-mm pore size) were used.

All N sources were broadcast at two rates (100 and 200 kg N ha^{-1}) and at two frequencies (every 20 and 40 d). These treatments provided a range in N applications of between 300 and 1200 kg ha^{-1} 120 d^{-1}. An extra pot with no added N was placed within each replication (0 N control). A supplemental nutrient solution (without N) was applied at 20 mL per pot every 20 d, and included the following rates for macronutrients (kg ha^{-1}): K (162), P (128), S (51), Ca (45), and Mg (38), plus a complete micronutrient supplementation (Turner and Hummel, 1992).

Clippings were cut with scissors every 3 or 4 d, keeping a cutting height of 1.5 cm. To remove and collect the clippings, pots were placed horizontally during the cutting process. Clippings were dried in a forced-air oven at 60°C for 48 h, weighed, and ground to pass through a 40 mesh (0.425-mm pore size). At the end of each experiment, the plugs were washed and separated into verdure (shoot material remaining after cutting) and thatch plus roots. These fractions were dried at 60°C for 72 h, weighed, and ground as described for the clippings. The sand and peat moss medium was air-dried, ground with a mortar and pestle, sieved using a 60 mesh (0.250-mm pore size), and a subsample was prepared for total Kjeldahl N analysis.

Total N content in the plant components (clippings, verdure, and thatch plus roots) and medium was measured. Thatch plus root consisted of stolons, rhizomes, true roots, and dead plant tissue. Nitrogen was extracted by the Kjeldahl acid digestion method (Bremner, 1996) using 0.2 g and 1.0 g for the plant and medium samples, respectively. Analyses were made colorimetrically for NH_4–N concentration using an automated Technicon Autoanalyzer II (Technicon Instruments, Tarrytown, NY). Leachates were collected and pooled during

Table 1. Greenhouse temperatures and light conditions per period and experiment.

Exp.	Period of growth	Dates (1997)	Natural light range		Temperature range	
			Sunrise	Sunset	Min.	Max.
			h		°C	
1†	1‡	27 Jan.–15 Feb.	0704–0649	1735–1753	16.7–20.0	28.6–42.0
	2‡	16 Feb.–8 Mar.	0648–0626	1754–1810	15.0–22.0	22.0–42.0
	3‡	9–28 Mar.	0625–0600	1811–1824	18.0–21.7	28.3–41.0
	4	29 Mar.–16 Apr.	0559–0536	1825–1837	14.1–18.0	28.0–33.9
	5	17 Apr.–6 May	0535–0516	1838–1852	12.1–20.8	26.8–37.8
	6	7–29 May	0515–0502	1852–1907	15.5–18.8	30.0–35.0
2§	1	23 July–11 Aug.	0516–0526	1911–1855	19.2–23.6	31.3–37.4
	2	12–31 Aug.	0527–0541	1857–1832	18.2–23.2	32.7–37.2
	3	1–20 Sept.	0542–0554	1831–1806	19.3–22.7	30.5–33.5
	4	21 Sept.–10 Oct.	0555–0607	1805–1740	14.4–20.5	27.1–30.3
	5	11–30 Oct.	0608–0623	1739–1718	7.9–20.3	25.6–29.8
	6	31 Oct.–19 Nov.	0623–0640	1717–1704	9.1–14.3	18.2–30.9

† Artificial light supplemented from 1630 to 2000 h, 250 to 300 μmol m^{-2} s^{-1}.
‡ Gas heater system.
§ Pad–fan cooling system.

six periods through each experiment (20-d intervals) and analyzed colorimetrically for NO_3–N concentration by the cadmium reduction column method using the autoanalyzer (Technicon Instruments Corporation, 1973).

The treatments were arranged in a 3 × 2 × 2 factorial (three N sources, two rates, and two frequencies) and distributed in a randomized complete block design with three replications. Clippings were pooled together every 20 d (six periods in total) to allow sufficient dry matter for tissue analysis. Nitrogen analyses were considered as repeated measurements and the Huynh–Feldt conditions were tested. Because the Huynh–Feldt conditions were satisfied, these data were analyzed as a split-plot (SAS Institute, 1990). The main plot was the 3 × 2 × 2 factorial and the period factor (total of six) was the subplot.

Plant samples were evaluated for N concentration, total N yield, N partitioning among tissues, and N recovery. Before the treatments started, a representative pot was removed and analyzed for N content of plant (verdure and thatch plus root) and growing medium fractions. This N value was considered as the initial N status in the system and was used for the N recovery estimation.With limited exceptions, there were no interactions among the main factors of N source, rate, and frequency. Thus, N sources were averaged across rates and frequencies, rates across sources and frequencies, and frequencies across sources and rates.

RESULTS AND DISCUSSION

Nitrogen Concentration

Average Clipping Nitrogen

The use of SCU and URE resulted in higher N concentrations in bermudagrass clippings (51.6 and 50.5 g N kg^{-1}) as compared with HYD (43.6 g N kg^{-1}) (Fig. 1, average of the two experiments). On average, clipping N concentration increased with N rate (45.3 and 51.8 g N kg^{-1} for 100 and 200 kg N ha^{-1}, respectively), and decreased with less frequent fertilizations, (51.7 and 45.3 g N kg^{-1} for the 20- and 40-d frequencies, respectively). Average clipping N concentration in Exp. 1 (in-

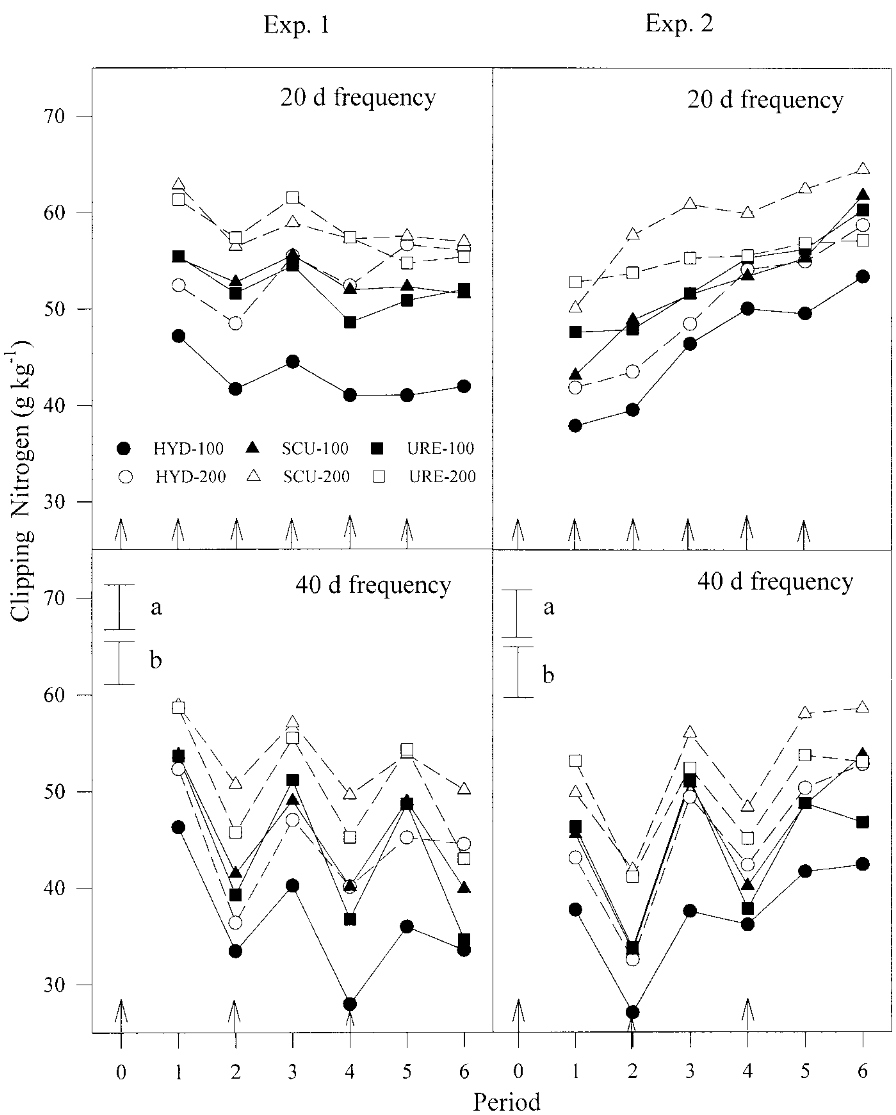

Fig. 1. Clipping N concentration measured at each 20-d period for 'Tifgreen' bermudagrass under three N sources (Hydroform, HYD; sulfur-coated urea, SCU; and urea, URE), two N rates (100 and 200 kg ha^{-1}), and two fertilization frequencies (every 20 and 40 d). Arrows represent time of N application. Each point represents the average of three observations. Vertical bars represent LSD_{05} for (*a*) treatments across periods and (*b*) treatments at the same or different period for both frequencies in each experiment.

creasing photoperiod) was 49.6 g N kg^{-1} as compared with 47.6 g N kg^{-1} in Exp. 2 (decreasing photoperiod).

Clipping Nitrogen Through Time

Average N concentration across the six 20-d periods differed between the experiments (Fig. 1). During Exp. 1 (long-day conditions), clipping N concentration gradually declined as the season progressed, as the increasing dry matter (DM) accumulation diluted the N concentration. In marked contrast, in Exp. 2 (decreasing photoperiod), clipping N concentration increased as the growing season progressed, since DM accumulation declined and the N was less diluted. The clipping N concentrations in both experiments are similar to those reported in other studies with bermudagrass (Snyder and Burt, 1985; Volk and Horn, 1975).

In both experiments, significant interactions among periods were found. In the 40-d frequency (but not 20-d frequency), clipping N concentration for all sources and rates showed a cyclical pattern (Fig. 1). That is, clipping N concentration (and growth) declined as medium N was gradually depleted at the end of each 40-d period. During the second experiment (decreasing photoperiod), differences among the N sources tended to narrow, as bermudagrass growth declined with the onset of autumnal environmental conditions. In addition, the characteristic cyclic pattern of N concentration (40-d frequency) was virtually eliminated between the fifth and sixth periods (Exp. 2), but was plainly evident under the greater photoperiod at this time (Exp. 1).

Verdure, Thatch Plus Root, and Growing Medium

At the end of the first experiment (long-day conditions), verdure N concentration ranged between 15.0 and 31.6 g N kg^{-1} (averaged data not presented), and overall, was greater in pots fertilized with URE than with SCU and HYD in Exp. 1 (Table 2). In Exp. 2 (decreasing photoperiod), verdure N concentration ranged from 15.0 to 28.4 g N kg^{-1} (averaged data not presented), but there were no differences among the N sources. As expected, in both experiments, verdure N concentration increased with the higher N rate and frequent fertilization. Nitrogen concentration in thatch plus roots was between 11.1 and 21.1 g N kg^{-1} (averages not shown), with an increasing trend at the high N rate and frequent fertilization (Table 2). During Exp. 1, N source did not affect thatch plus root N concentration. In Exp. 2, however, URE resulted in a greater thatch plus root N concentration than with HYD. At the end of each experiment, statistical differences for main factor effects on growing medium N concentration were found only for frequencies in the first experiment, with the 20-d application interval providing the higher N concentration (Table 2).

Table 2. Main effect means for verdure, thatch plus root, and growing medium N concentration measured 120 d after start of fertilization for 'Tifgreen' bermudagrass under three N sources, two N rates, and two fertilization frequencies.

Factor	Verdure Exp. 1	Verdure Exp. 2	Thatch + root Exp. 1	Thatch + root Exp. 2	Growing medium Exp. 1	Growing medium Exp. 2
	g N kg^{-1}					
N source†						
HYD	21.4b‡	19.9 NS	17.6 NS	13.3b	0.317 NS	0.270 NS
URE	24.9a	23.4	16.1	15.6a	0.298	0.251
SCU	21.8b	26.6	15.2	15.1ab	0.286	0.276
N rate (kg ha^{-1})						
100	19.6b	20.0b	14.8b	13.6b	0.286 NS	0.272 NS
200	25.9a	23.2a	17.8a	15.8a	0.315	0.259
N frequency (d)						
20	26.8a	23.2a	18.5a	16.0a	0.323a	0.259 NS
40	18.6b	20.1b	14.1b	13.4b	0.278b	0.272
Initial conditions§	21.9	14.2	11.2	8.8	0.26	0.2

† HYD, Hydroform; URE, urea; SCU, sulfur-coated urea.
‡ Means within columns for N source, rate, or frequency followed by the same letter are not significantly different (Tukey; $P \leq 0.05$). NS = nonsignificant.
§ Nitrogen concentrations in verdure, thatch + root, and growing medium before N treatments started.

Nitrogen Yield

Total Clipping Nitrogen Yield

Total N yield or removal by clippings in both experiments followed the same trend as did N concentration. The highest average total (accumulated) clipping N yield was provided by SCU (38.1 and 31.0 g N m^{-2}) and URE (35.3 and 29.4 g N m^{-2}), and the lowest by HYD (22.5 and 17.6 g N m^{-2}), in Exp. 1 and 2, respectively. Also, the high N rate and more frequent fertilization resulted in greater total N yield than with the low rate and frequency.

Clipping Nitrogen Yield Through Time

During the first experiment (long-day conditions), clippings removed more N at the end of the growing time (Fig. 2, Periods 5 and 6). The low N yield during the fourth period may have resulted from relatively low greenhouse nighttime minimum temperatures (mean of 16°C). For the second experiment (decreasing photoperiod), the trend was for more clipping N yield during the first half of the experiment rather than during the second half. Thus, as growth became increasingly limited with decreasing photoperiod and temperature, parallel reduction in clipping N yield (N demand) also occurred.

Interaction among N source, rate, frequency, and period resulted because of the repeated cyclical trend found on all the sources and both rates at the 40-d frequency, particularly in Exp. 1 (Fig. 2). At the 20-d frequency, there was less of a cyclic trend for all treatments, and at the low rate in Exp. 1, clipping N yield with HYD was significantly lower than any other treatment combination. This difference was not so apparent, however, at the 40-d frequency of Exp. 1, especially at Periods 2, 4, and 6, when N availability was limited. The cyclical trend was also present during Exp. 2 up to the fourth period (40-d frequency), after which time the decreasing photoperiod (<12 h) essentially eliminated the growth response to applications of fertilizer N.

Verdure, Thatch Plus Roots, and Growing Medium

Verdure N yield in the first experiment (long-day conditions) was significantly affected by N source, rate, and frequency (Table 3). The highest average N yield

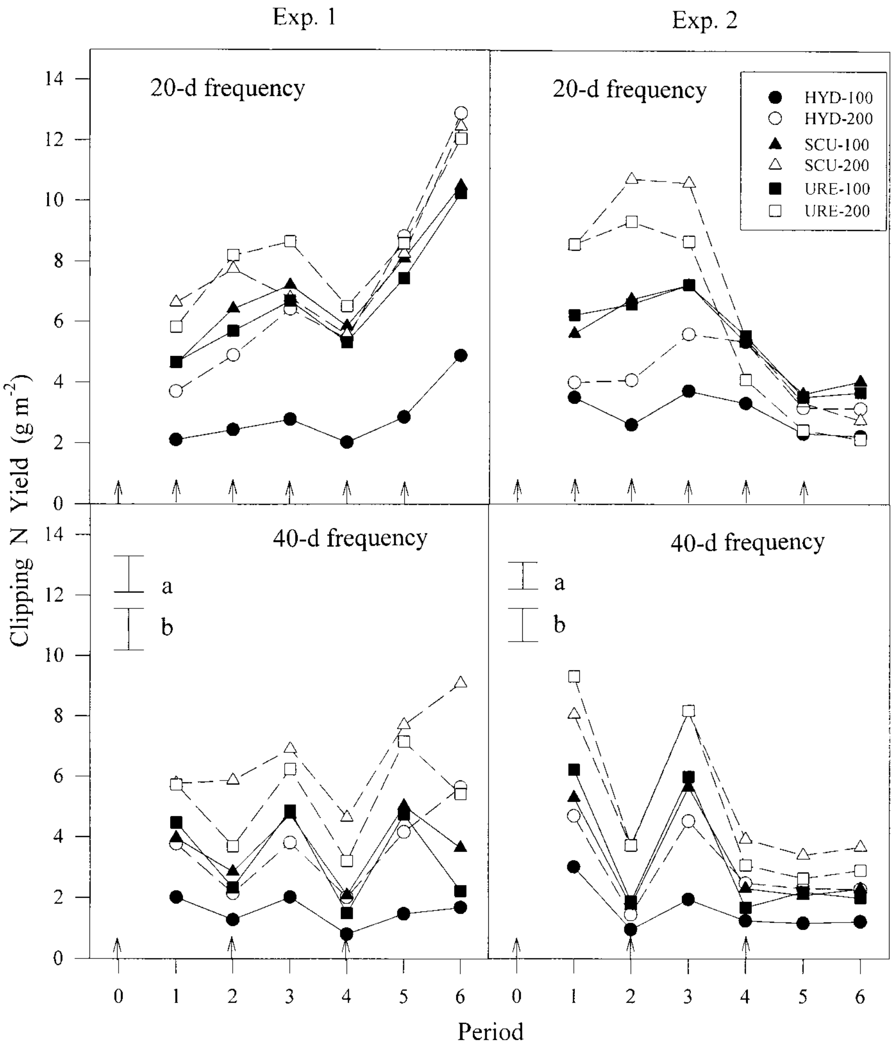

Fig. 2. Clipping N yield measured at each 20-d period for 'Tifgreen' bermudagrass under three N sources (Hydroform, HYD; sulfur-coated urea, SCU; and urea, URE), two N rates (100 and 200 kg ha^{-1}), and two fertilization frequencies (every 20 and 40 d). Arrows represent time of N application. Each point represents the average of three observations. Vertical bars represent LSD_{05} for (*a*) treatments across periods and (*b*) treatments at the same or different period for both frequencies in each experiment.

was obtained with SCU and the lowest with HYD. For Exp. 2 (decreasing photoperiod), no differences among sources were detected. On average, 40% more N yield was obtained from verdure in the first experiment than in the second experiment. The high N rate and more frequent fertilization increased verdure N yield in both experiments. However, in Exp. 2, average N yield with SCU and URE was greater with the lower frequency than with the higher frequency (data not presented).

Thatch plus root N yield was affected only by rate and frequency and only during Exp. 1 (Table 3). Greater N yield occurred with the high N rate and more frequent fertilization. During Exp. 2, main effects were absent. No effects of any of the three factors on growing medium N yield were detected (Table 3).

Leachate Nitrate Nitrogen

As with clippings, leachates were pooled over six periods (20 d each) and analyzed through time. Overall trends in leaching NO_3–N concentration differed between experiments (Fig. 3). During Exp. 1 (long-day conditions), all NO_3–N concentrations were below the USEPA limit of 10 mg L^{-1}. For sources, the trend was unexpected, as the highly soluble URE showed the lowest average leachate NO_3–N value, whereas the highest concentration corresponded to HYD, the least soluble source. Leachate NO_3–N concentrations were not significantly affected by rate or frequency. For periods, there was no apparent trend, except that the low leachate NO_3–N concentration at Period 3 preceded a measurable average increase in leachate NO_3–N concentration at Period 4, which corresponded to the transient reduction in clipping N demand.

In Exp. 2 (decreasing photoperiod), means for all the main factors (N source, rate, frequency, and time) followed a more expected trend (Fig. 3). A significantly greater leaching NO_3–N concentration was detected with URE and SCU, and over all sources, there were higher NO_3–N concentrations at the high rate and frequent fertilization. Also, the greatest concentrations were found at the end of the growing period (Periods 5 and 6), when average NO_3–N concentrations were well

Table 3. Main effect means for verdure, thatch plus root, and growing medium N yield measured 120 d after start of fertilization for 'Tifgreen' bermudagrass under three N sources, two N rates, and two fertilization frequencies.

Factor	Verdure		Thatch + root		Growing medium†	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
	g N m^{-2}					
N source‡						
HYD	8.6b§	6.2 NS	28.4 NS	23.2 NS	68.1 NS	58.1 NS
URE	9.4ab	7.1	25.4	26.2	64.1	53.9
SCU	10.2a	6.8	24.6	24.6	61.5	59.3
N rate (kg ha^{-1})						
100	8.0b	6.1b	23.7b	23.2 NS	67.7 NS	58.5 NS
200	10.7a	7.3a	28.5a	26.2	61.5	55.6
N frequency (d)						
20	11.4a	6.9a	30.8a	25.9 NS	69.4 NS	55.8 NS
40	7.4b	6.6b	21.5b	23.5	59.8	58.4
Initial conditions¶	1.4	1.5	13.0	10.6	55.6	41.9

† Yield expressed on the basis of equivalent sample area. Pot area = 0.01767 m^2, volume = 5.0 L, growing medium dry weight = 3.8 kg pot^{-1}.
‡ HYD, Hydroform; URE, urea; SCU, sulfur-coated urea.
§ Means within columns for N source, rate, or frequency followed by the same letter are not significantly different (Tukey; $P \leq 0.05$). NS = nonsignificant.
¶ Nitrogen yield in verdure, thatch + root, and growing medium before N treatments started.

Table 4. Total plant N removal, adjusted plant N removal (totals minus initial verdure and thatch plus root N), and plant N recovery for 'Tifgreen' bermudagrass under three N sources, two N rates, and two fertilization frequencies.

Factor	Plant N removal		Adjusted plant N removal†		Plant N recovery‡	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
	g N m^{-2}				%	
N source§						
HYD	59.5b¶	47.0b	45.2b	34.9b	66.9b	56.1b
SCU	72.8a	62.5a	58.5a	50.3a	94.8a	85.7a
URE	70.1a	62.7a	55.8a	50.9a	89.4a	85.7a
N rate (kg ha^{-1})						
100	57.1b	51.2b	42.7b	39.1b	93.4a	90.6a
200	77.9a	63.6a	63.6a	51.4a	74.1b	62.7b
N frequency (d)						
20	82.0a	63.6a	67.7a	51.4a	80.9 NS	62.7b
40	53.0b	51.2b	38.6b	39.1b	86.6	90.6a

† Total plant N removal − initial (verdure and thatch + root) N yield.
‡ (Adjusted plant N removal/total applied N) × 100.
§ HYD, Hydroform; SCU, sulfur-coated urea; URE, urea.
¶ Means within columns for N source, rate, or frequency followed by the same letter are not significantly different (Tukey; $P \leq 0.05$). NS = nonsignificant.

above the USEPA standard limit. Thus, in comparison with Exp. 1, the reduced N demand and a slightly greater leaching fraction (9.1 vs. 5.3%) combined to increase NO_3–N leaching of the more soluble N sources (URE and SCU).

All the possible interactions occurred in Exp. 2. For example, the source × period interaction occurred largely at the end of the growing season, when leaching NO_3–N values with SCU and URE (high N rate) rose to levels 10 to 20 times the standard limit under the 20-d fertilization frequency. A similar range was observed with cool-season species (Brown et al., 1982), although the bermudagrass study by Snyder et al. (1984) did not show leachate NO_3–N levels greater than the USEPA limit. At the end of Exp. 2 (Periods 5 and 6), the observed increases in NO_3–N leachate concentration probably occurred because bermudagrass N uptake decreased as the grass was progressing into its dormancy period.

Nitrogen Removal and Recovery

Nitrogen removal by the plant (clippings, verdure, and thatch plus roots) is presented in Table 4 as total N removal and adjusted N removal (adjusted for initial N content in verdure and thatch plus roots prior to the beginning of fertilization treatment). Plant N removal was greater in Exp. 1 than in Exp. 2, since Exp. 1 was conducted under long-day conditions and higher minimum temperatures, which resulted in greater plant growth, and therefore increased plant N uptake. For both experiments, N source, rate, and application frequency significantly acted upon plant N removal. On average, adjusted plant N yields were 53.2 and 45.2 g m^{-2} for Exp. 1 and 2, respectively. In both experiments, there was more N yield for SCU and URE than for HYD, and greater N yield at the higher N rate and frequency. Only main factor effects were found, with no interactions.

The verdure and thatch plus root initial N conditions (g m^{-2}, Table 3) were subtracted from the total plant N removal to obtain an adjusted plant N removal attributable only to fertilization, to estimate total plant fertilizer N recovery (Table 4). The total fertilizer N applied ranged from 30 to 120 g m^{-2} 120 d^{-1}. Total plant fertilizer N recovery in both experiments was 23 to 32% greater with SCU and URE than with HYD. Also, plant N recovery was 19 and 28% greater with the low N rate than for the high N rate (Exp. 1 and 2, respectively), which is consistent with the general concept of less N recovery efficiency by turfgrass with increasing fertilizer N application rate (Hesketh et al., 1995). The application frequency effect was significant only in the second experiment, with 28% more N recovery with the 40-d application frequency than with the 20-d frequency.

The interaction source × rate for total plant N recovery occurred in both experiments (Fig. 2). In the first experiment, N recovery substantially increased with increased HYD rate under both 20-d and 40-d application frequencies. This increase was less noticeable with SCU and URE. The responsiveness to HYD may have resulted from the low N availability of this highly insoluble N source, with a temporal plant N deficiency stress at the end of the 40-d period. Once the new N application was made, bermudagrass N uptake and recovery apparently increased above the average in the other treatments (Bowman et al., 1989; Hole et al., 1990).

Total plant N recovery estimates were made without a labeled N isotope, and N recoveries occasionally rose above 100% due to measurement errors. However, the average total plant N recoveries from the fertilizer (Table 4) were 84 and 77% in Exp. 1 and 2, respectively. These values are somewhat greater than those reported in cool-season turf species. For example, Starr and DeRoo (1981) reported total plant ^{15}N recovery values of approximately 50 to 60% [from applied $(NH_4)_2SO_4$] in a Kentucky bluegrass–red fescue (*Festuca rubra* L.) mixture. Similarly, Miltner et al. (1996) found that 66% of the applied ^{15}N-labeled urea fertilizer to Kentucky bluegrass was recovered by the whole plant, with about 50% found in clippings.

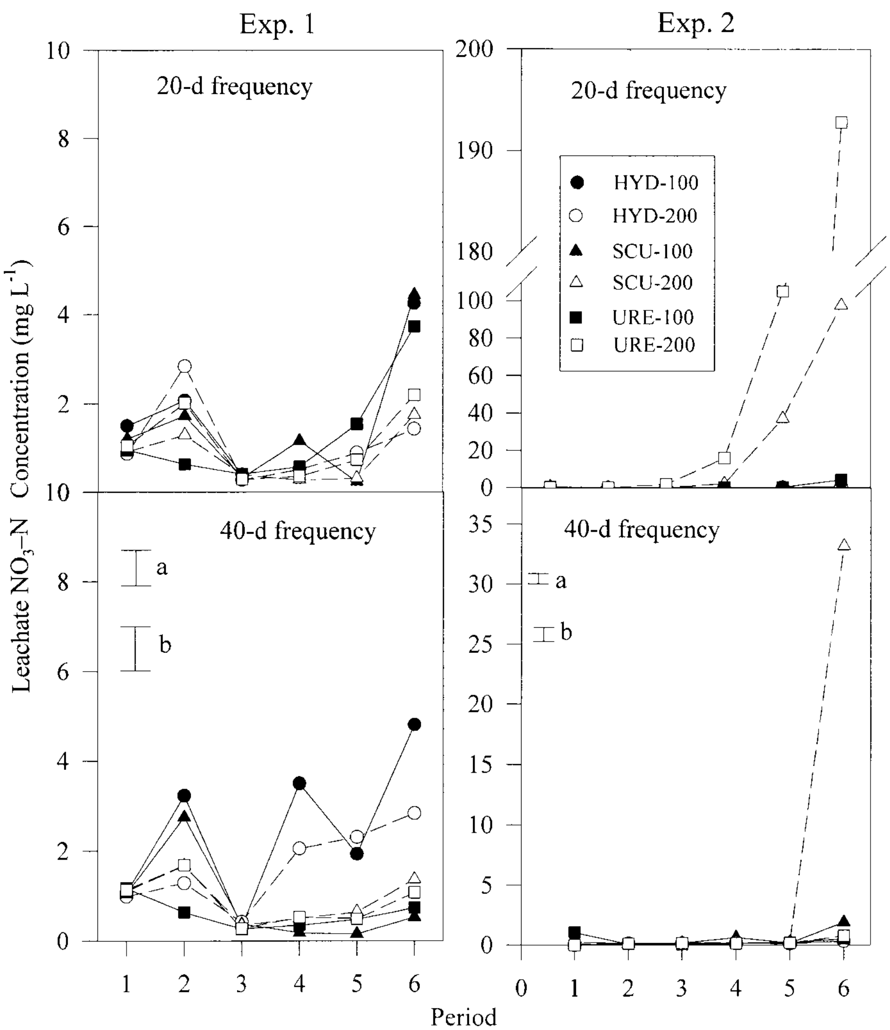

Fig. 3. Leaching NO_3–N concentration measured at each 20-d period for 'Tifgreen' bermudagrass under three N sources (Hydroform, HYD; sulfur-coated urea, SCU; and urea, URE), two N rates (100 and 200 kg ha^{-1}), and two fertilization frequencies (every 20 and 40 d). Arrows represent time of N application. Each point represents the average of three observations. Vertical bars represent LSD_{05} for (*a*) treatments across periods and (*b*) treatments at the same or different period for both frequencies in each experiment.

There was a greater percentage of applied fertilizer N recovery with SCU and URE than with HYD with the lower N rate and less frequent fertilization (Exp. 2 only). Greater recovery efficiency with the lower N rate is consistent with findings reported on Kentucky bluegrass and Chewing's fescue [*Festuca rubra* L. subsp. *fallax* (Thuill.) Nyman] (Hesketh et al., 1995).

Partitioning of Plant Nitrogen

Of the adjusted plant N removal, an average of 58 to 60% of the total plant N was found in clippings, 12 to 16% in verdure, and 24 to 30% in thatch plus roots (Table 5). Nitrogen source affected the N partitioning only in Exp. 1 (long-day conditions), in that there was more total plant N in clippings using SCU and URE than with HYD, whereas the reverse occurred with verdure and thatch plus root N. Thus, with greater N availability (e.g., SCU and URE), more N was diverted to clippings. Under lower N availability (HYD), the N was directed to verdure, thatch, and roots (Adams et al., 1973; Bowman et al., 1989), because the low solubility and reduced N availability of HYD was associated with reduced clipping biomass production and N demand. The decreasing photoperiod and temperature in the second experiment limited these bermudagrass responses to the different N sources.

Of the applied N fertilizer, an average of 43 to 51% was recovered in clippings, 9 to 13% in verdure, and 20 to 25% in thatch plus roots (Table 5). In both experiments, N source, rate, and frequency main effects on N recovery were more evident in clippings and verdure. The general trend in most of the treatments was a decrease in clipping N allocation and fertilizer N recovery as N rate increased (SCU and URE), except for HYD at the 20-d frequency, where a large increase in N allocation to clippings occurred with the increased N rate (Fig. 2).

SIGNIFICANCE AND APPLICABILITY OF FINDINGS

Concerns related to potential NO_3–N pollution will probably necessitate changes in current N fertilization

Table 5. Relative distribution (%) of adjusted plant N removal among the plant components, and the contribution (%) of each plant component to plant recovery of applied N for 'Tifgreen' bermudagrass under three N sources, two N rates, and two fertilization frequencies.

Factor	Clipping Rem.†	Clipping Rec.	Verdure Rem.	Verdure Rec.	Thatch + root Rem.	Thatch + root Rec.
	%					
			Exp. 1			
N source‡						
HYD	50.7b§	32.6c	17.7a	11.5b	31.6a	22.8 NS
SCU	66.1a	62.9a	15.2ab	14.2a	18.7b	17.7
URE	64.2a	56.9b	14.7b	13.0ab	21.1b	19.5
N rate (kg ha^{-1})						
100	60.0 NS	56.4a	17.0a	15.0a	22.9 NS	22.0 NS
200	60.6	45.2b	14.7b	10.8b	24.7	18.1
N frequency (d)						
20	58.0 NS	47.1b	14.8b	11.9b	27.1a	21.9 NS
40	62.6	54.5a	16.9a	13.9a	20.5b	18.2
			Exp. 2			
N source						
HYD	52.9 NS	28.0b	14.0 NS	7.5b	33.1 NS	20.6 NS
SCU	62.0	51.2a	11.0	9.8ab	27.0	24.7
URE	58.3	50.0a	11.5	10.4a	30.2	27.8
N rate (kg ha^{-1})						
100	56.5 NS	50.2a	13.1 NS	11.4a	30.4 NS	29.0a
200	58.9	35.9b	11.2	7.1b	29.8	19.7b
N frequency (d)						
20	60.3 NS	37.2b	10.6b	6.3b	29.1 NS	19.2b
40	55.1	48.9a	13.7a	12.2a	31.1	29.5a

† Adjusted plant N removal (Rem.) and plant component N recovery (Rec.).
‡ HYD, hydroform; SCU, sulfur-coated urea; URE, urea.
§ Means within columns for N source, rate, or frequency followed by the same letter are not significantly different (Tukey; $P \leq 0.05$). NS = nonsignificant.

management that will aid in developing more environmentally sustainable turfgrass plantings. Even a cursory evaluation of turfgrass-related trade journals is a strong testimony for the pressing need to reduce environmental effect of N fertilization in turfgrass systems.

There is a scarcity of technical data on factors governing fertilizer N use efficiency and losses in warm-season turfgrasses. In this report, we provided quantitative information that will contribute to the limited database, most notably to bermudagrasss culture. The results bring attention to the multitude of factors that play a determinant role in the efficiency of use of fertilizer N and the attendant risk of NO_3–N leaching losses in bermudagrass turf. These factors include fertilizer N source, N rate, N solubility, season of year, frequency of application, irrigation, growth stage, and stand vigor. One of the more salient lessons we illustrate is that high N applications at the end of the growing season (e.g., autumn), a widely used but controversial practice of warm-season turf managers in the southern USA (Goatley et al., 1998), clearly increases the risk of N losses by leaching.

Our findings imply a tradeoff between stand vigor and color and NO_3–N leaching risk with the slow-release N products. That is, URE and SCU tend to enhance vigor and greening (through more rapid N availability and N uptake), but they also increase the risk of N loss. Conversely, the sparingly soluble HYD does not promote as much vigor and color but does seem to minimize the risk of N leaching loss at equivalent N application rates and frequencies. This type of N source may be highly beneficial from the view of abating potential NO_3 contamination of ground water, because in our study, it did decrease or essentially eliminate the loss of NO_3–N through the leaching fraction under more frequent application and reduced N demand periods (Fig. 3, Exp. 2).

In late fall (later stages of Exp. 2, late October through November), N yield was hardly affected by N source at a given N rate (Fig. 2). This means that a product such as HYD could be effective in improving fall N fertilization efficiency without a major sacrifice in vigor of the grass. Even under longer photoperiods more conductive to growth (Exp. 1), it appeared that higher HYD application rate and frequency overcame its lack of solubility so that N yield was not greatly reduced below that of SCU and URE.

For practical turfgrass management, high clipping growth rates increase maintenance costs. Therefore, turf quality becomes a major factor determining management practices. It appears that even with slowly soluble N sources (e.g., HYD), we may be able to achieve a proper balance between N application rate and frequency that provides satisfactory vigor and color while minimizing NO_3 leaching loss potential. The use of highly soluble N sources in bermudagrass (e.g., URE) is still a viable practice, but at the end of the growing season, heavy irrigation with high N rates will result in a potential risk of NO_3–N losses by leaching.

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REFERENCES

Adams, W.A., P.J. Bryan, and G.E. Walker. 1973. Effects of cutting height and nitrogen nutrition on growth pattern of turfgrasses. p. 131–144. *In* E.C. Roberts (ed.) Proc. 2nd Int. Turf. Res. Conf., Blacksburg, VA. 19–21 June 1973. ASA, Madison, WI.

Bowman, D.C., J.L. Paul, and W.B. Davis. 1989. Nitrate and ammonium uptake by nitrogen-deficient perennial ryegrass and Kentcky bluegrass turf. J. Am. Soc. Hortic. Sci. 114:421–426.

Bremner, J.M. 1996. Nitrogen—Total. p. 1085–1121. *In* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Brown, K.W., J.C. Thomas, and R.L. Duble. 1982. Nitrogen source effect on nitrate and ammonium leaching and runoff from greens. Agron. J. 74:947–950.

Exner, M.E., M.E. Burbach, D.G. Watts, R.C. Sherman, and R.F. Spalding. 1991. Deep nitrate movement in the unsaturated zone of a simulated urban lawn. J. Environ. Qual. 20:658–662.

Goatley, J.M., Jr., V.L. Maddox, and K.L. Hensler. 1998. Late-season applications of various nitrogen sources affect color and carbohydrate content of 'Tiflawn' and Arizona common bermudagrass. HortScience 33:692–695.

Hesketh, E.S., R.J. Hull, and A.J. Gold. 1995. Estimating non-gaseous nitrogen losses from established turf. J. Turf. Manage. 1:17–30.

Hole, D.J., A.M. Emran, Y. Fares, and M.C. Drew. 1990. Induction of nitrate transport in maize roots and kinetics of influx, measured with nitrogen-13. Plant Physiol. 93:642–647.

Hummel, N.W., Jr., and D.V. Waddington. 1981. Evaluation of slow-release nitrogen sources on 'Baron' Kentucky bluegrass. Soil Sci. Soc. Am. J. 45:966–970.

Liu, H., R.J. Hull, and D.T. Duff. 1997. Comparing cultivars of three

cool-season turfgrasses for soil water NO_3 concentration and leaching potential. Crop Sci. 37:526–534.
Miltner, E.D., B.E. Branham, E.A. Paul, and P.E. Rieke. 1996. Leaching and mass balance of ^{15}N-labeled urea applied to a Kentucky bluegrass turf. Crop Sci. 36:1427–1433.
Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. J. Environ. Qual. 17:124–130.
Mosdell, D.K., and R.E. Schmidt. 1985. Temperature and irrigation influences on nitrate losses of *Poa pratensis* L. turf. p. 487–494. *In* F. Lemaire (ed.) Proc. 5th Int. Turf. Res. Conf., Avigon, France. 1–5 July 1985. INRA, Versailles, France.
Nelson, K.E., A.J. Turgeon, and J.R. Street. 1980. Thatch influence on mobility and transformation of nitrogen carriers applied to turf. Agron. J. 72:487–492.
Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1–14.
Rieke, P.E., and B.G. Ellis. 1973. Effects of nitrogen fertilization on nitrate movements under turfgrass. p. 120–130. *In* E.C. Roberts (ed.) Proc. 2nd Int. Turf. Res. Conf., Blacksburg, VA. 19–21 June 1973. ASA, Madison, WI.
SAS Institute. 1990. SAS/STAT user's guide. Volume 2, GLM-VARCOMP. SAS Inst., Cary, NC.
Snyder, G.H., B.J. Augustin, and J.M. Davidson. 1984. Moisture sensor-controlled irrigation for reducing N leaching in bermudagrass turf. Agron. J. 76:964–969.
Snyder, G.H., and E.O. Burt. 1985. Nitrogen sources for fertigation of bermudagrass turf. p. 557–565. *In* F. Lemaire (ed.) Proc. 5th Int. Turf. Res. Conf., Avigon, France. 1–5 July 1985. INRA, Versailles, France.
Snyder, G.H., E.O. Burt, and J.M. Davidson. 1977. Nitrogen leaching in bermudagrass turf: Daily fertigation vs. tri-weekly conventional fertilization. p. 185–193. *In* J.B. Beard (ed.) Proc. 3rd Int. Turf. Res. Conf., Munich, Germany. ASA, Madison, WI.
Spalding, R.F., and M.E. Exner. 1993. Occurrence of nitrate in groundwater—A review. J. Environ. Qual. 22:392–402.
Starr, J.L., and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Sci. 21:531–536.
Technicon Instruments Corporation. 1973. Technicon Autoanalyzer II. Industrial Method 100-70W. Nitrate and nitrite in water and wastewater. Technicon Industrial Systems, Tarrytown, NY.
Turner, T.R., and N.W. Hummel, Jr. 1992. Nutritional requirements and fertilization. p. 387–439. *In* D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison WI.
Volk, G.M., and G.C. Horn. 1975. Response curves of various turfgrasses to application of several controlled-release nitrogen sources. Agron. J. 67:201–204.

Summary of Well Water Sampling in California to Detect Pesticide Residues Resulting from Nonpoint-Source Applications

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ABSTRACT

This report summarizes well sampling protocols, data collection procedures, and analytical results for the presence of pesticides in ground water developed by the California Department of Pesticide Regulation (DPR). Specific well sampling protocols were developed to meet regulatory mandates of the Pesticide Contamination Prevention Act (PCPA) of 1986 and to provide further understanding of the agronomic, chemical, and geographic factors that contribute to movement of residues to ground water. The well sampling data have formed the basis for the DPR's regulatory decisions. For example, a sampling protocol, the *Four-Section Survey*, was developed to determine if reported detections were caused by nonpoint-source agricultural applications, a determination that can initiate formal review and subsequent regulation of a pesticide. Selection of sampling sites, which are primarily rural domestic wells, was initially based on pesticide use and cropping patterns. Recently, soil and depth-to-ground water data have been added to identify areas where a higher frequency of detection is expected. In accordance with the PCPA, the DPR maintains a database for all pesticide well sampling in California with submission required by all state agencies and with invitations for submission extended to all local and federal agencies or other entities. To date, residues for 16 active ingredients and breakdown products have been detected in California ground water as a result of legal agricultural use. Regulations have been adopted for all detected parent active ingredients, and they have been developed regardless of the level of detection.

In 1979, residues of 1,2-dibromo-3-chloropropane (DBCP) were detected in California well water. This discovery demonstrated the potential effect that agricultural applications of pesticides could have on California's ground water supplies (Peoples et al., 1980). Prior to this time, movement of pesticides to ground water was considered unlikely because of dilution effects, low water solubility, high vapor pressure, rapid degradation, and binding to soil. After DBCP was detected, the Department of Pesticide Regulation (DPR, formerly the Division of Pest Management in the California Department of Food an Agriculture) conducted well sampling to determine the presence and geographical distribution of high use pesticides in California ground water. These surveys indicated that the contamination was more prevalent than originally anticipated.

The Pesticide Contamination Prevention Act (PCPA) was enacted into law in 1986 (Connelly, 1986). The law resulted in a shift of well sampling objectives because data were now needed to identify and support regulatory activities. Prior to the PCPA, concentrations of DBCP and ethylene dibromide (EDB) in well water were determined to pose a hazard, so the director of the California Department of Food and Agriculture made the decision to suspend statewide use. Subsequent active ingredients detected in well water were subjected to a formal review process that was prescribed in the

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Abbreviations: ACET, 2-amino-4-chloro-6-ethylamino-*s*-triazine; 1,2-D, 1-2-dichloropropane; DACT, 2,4-diamino-6-chloro-*s*-triazine; DBCP, 1,2-dibromo-3-chloropropane; DHS, California Department of Health Services; DPR, Department of Pesticide Regulation, California Environmental Protection Agency; EDB, ethylene dibromide; MCL, maximum contaminant level; MDL, minimum detection limit; PCPA, Pesticide Contamination Prevention Act; PMZ, pesticide management zones; TPA, 2,3,5,6-tetrachloroterephthalic acid; WIBD, Well Inventory Data Base.