Dry Weight Production and Nitrogen Efficiency Traits in Kentucky Bluegrass Cultivars in Nutrient Solution and Soil

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ABSTRACT

Because of the importance of such factors as appearance and vigor in turf management, genetic selection of Kentucky bluegrass (*Poa pratensis* L.) is often conducted at high levels of N application. This process can mask potential differences between genotypes in N efficiency, especially under low N levels. The case is also made that because soil is the medium in which plant selections ultimately must perform, cultivar screening for N efficiency in solution culture should relate to results in soil. This study was conducted to evaluate N-utilization efficiency (NUE—mg plant dry matter mg^{-1} plant N) in six bluegrass cultivars at low (0.2, 0.7 m*M* NO_3–N) and high (3.5 m*M* NO_3–N) levels of N supply in nutrient solution culture (nutriculture) and soil. With high N supply, total plant N accumulation and N-root uptake efficiency (NRE—mg plant N g^{-1} root dry matter) increased in each cultivar, while NUE and shoot efficiency ratio (SER—mg shoot dry matter mg^{-1} shoot N) decreased, with the magnitude and relative response dependent on genotype and medium. As a group, as well as individually, cultivars Asset, Dawn, and Trenton were higher yielding, more responsive to increasing solution N concentration, and more efficient (NUE) at low levels of N supply than cultivars Limousine, Barzan, or Midnight. Under low N supply, NUE in nutriculture ranged from 26.2 (g plant dry weight mg^{-1} N) in Limousine to 40.1 in Asset, and in soil from 63.6 in Midnight to 77.4 in Asset. Differences in NUE among cultivars were more associated with shoot efficiency than with root absorption efficiency. Despite noticeably higher NUE in soil than in nutriculture, and significant effects of N fertility, genotypic differences in the various N efficiency traits in solution culture were also apparent in soil. The results suggest that NUE in Kentucky bluegrass can be enhanced by cultivar selection under low-N conditions. While the similarities of the actual N conditions between nutriculture and soil remain in question, it appears that solution culture can be used as an effective surrogate for characterizing NUE in divergent types of bluegrass cultivars.

GIVEN the current concern about NO_3^- pollution of groundwater sources from agriculturally based fertilizer leaching and runoff, development of plant cultivars with improved N efficiency is becoming a major thrust in many plant breeding programs. For a given genotype, nutrient efficiency is reflected by the ability to produce high yield in a soil that is limited in one or more mineral nutrients for a standard genotype (Graham, 1984). Commonly, N efficiency in plants is expressed as NUE, or biomass produced per unit of plant N. Efficient genotypes produce more dry weight when compared with inefficient genotypes at an equal unit of absorbed N.

Differences among genotypes within species for NUE have been reported in corn (*Zea mays* L.) (Anderson et al., 1984; Kamprath et al., 1982), millet [*Pennisetum glaucum* (L.) R. Br.] (Alagarswamy and Bidinger, 1987), sorghum [*Sorghum bicolor* (L.) Moench] (Maranville et al., 1980), pumpkin (*Cucurbita moschata* Poir.) (Swiader et al., 1994), tomato (*Lycoperiscon esculentum* Mill.) (Gerloff, 1976; O'Sullivan et al., 1974), and wheat (*Triticum aestivum* L.) (Cox et al., 1985). Gerloff (1976) noted that efficient and inefficient snapbean (*Phaseolus vulgaris* L.) and tomato strains differed in yield as much as 44% per unit of absorbed N. Among 146 naturally occurring strains of tomatoes, as much as 45% difference in dry weight production per unit of N absorbed was observed under various levels of N stress (O'Sullivan et al., 1974). Grain sorghum hybrids in a field study showed a 20% difference in dry matter production per unit N uptake (Maranville et al., 1980). Saric and Krstic (1984) reported more potential differences in NUE among cultivars within a species than across several crop species. Alagarswamy and Bidinger (1987) screened 20 pearl millet genotypes grown in field conditions, and found little difference in total N uptake, yet significant differences in total above-ground biomass produced.

When evaluating plant differences in NUE, however, the results must be considered in relation to the level of N supply. Genotypes with relatively good ability to acquire and utilize N under low N levels may not be responsive to increased N supply, and conversely, genotypes with good ability to absorb and utilize N under high N levels may be inefficient users at low N supply. In studies with corn, Moll et al. (1982) divided N efficiency (grain produced per unit of available soil N) in terms of two components: absorption efficiency (total plant N accumulated per unit of N supplied) and utilization efficiency (total grain dry matter produced per unit of plant N). Causes of variation in N efficiency in terms of these two components were found to differ between the levels of N supply and among genotypes. At low N supply, differences among genotypes in N efficiency were due to variation in N utilization, whereas at high N supply, genotypic differences in N efficiency were due mainly to variation in N-uptake efficiency. In a related study, higher N efficiency of one corn hybrid as compared to two other hybrids was because it was higher in both N-use components (Kamprath et al., 1982).

While N nutrition of Kentucky bluegrass has been extensively studied in relation to yield and quality, relatively few studies emphasize the effects of cultivar on NUE. Because of the importance of such factors as appearance and vigor in turf management, genetic selection of bluegrass is often conducted at high levels of N application in order to eliminate N as a variable (USDA and National Turfgrass Federation, 1996). This process can mask potential differences between genotypes for NUE under low N applications. Based on findings for

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Abbreviations: NUE, N-utilization efficiency; NRE, N-root uptake efficiency; Ns, nitrogen supply; SER, shoot efficiency ratio.

other plant species where cultivar variation within species for NUE can be quite significant (see above), it appears that it may be possible to develop highly efficient bluegrass cultivars adapted to either high or low N nutrition, or both, without sacrificing vigor and quality.

The objective of this study was to evaluate six bluegrass cultivars, differing in biomass production potential, for NUE at low (0.2, 0.7 m*M* NO_3^-–N) and high (3.5 m*M* NO_3^-–N) levels of N supply. Additionally, the case was made that because soil is the medium in which plant selections ultimately must perform, cultivar screening for nutrient efficiency in solution culture (nutriculture) should relate to results in soil (Gerloff, 1987). While the nutriculture method facilitates screening large numbers of plants and eliminates some of the physiochemical complexities involved in soil studies, system-induced variations in nutrient availability, as well as plant morphological, anatomical, and physiological factors with nutriculture might result in genotypic variation in NUE different from those which would occur in soil. Subsequently, a secondary objective of this study was to compare the effects of screening procedures, namely nutriculture versus a soil–sand medium, on cultivar differences in NUE in Kentucky bluegrass.

MATERIALS AND METHODS

The six cultivars used in this study were selected from three screening trials (Bertauski et al., 1993) involving 25 cultivars that identified two groups of Kentucky bluegrass genotypes based on their dry matter potential under varying N conditions: "N-non-adapted" cultivars (Limousine, Barzan, Midnight) showed low biomass response to N; while "N-adapted" cultivars (Asset, Trenton, Dawn) were high yielding with vigorous response to N. All experiments were conducted in a greenhouse with air temperatures maintained at 22 ± 5°C during the day and 20 ± 3°C at night. High intensity discharge lamps with mercury-halide bulbs were used to supplement natural light and provide a 14/10-h day/night photoperiod with a photosynthetic photon flux density of ~400 μmol m^{-2} s^{-1} during the daylength period.

Nutriculture Experimentation

Seeds of each cultivar were sown by hand in plastic trays (25 by 52 cm) containing moistened medium-grade vermiculite. After 13 d, when germination and seedling establishment were complete, 60 plants of each cultivar were removed from the germination trays, their roots washed free of all media, and transplanted into polyethylene tubs (51 by 38 by 13 cm) containing 15 L of one-quarter-strength aerated Hoagland nutrient solution (Hoagland and Arnon, 1950). The seedling plants were supported by foam polyurethane plugs which were placed in holes (7-mm diam.) 1 cm apart cut in a styrofoam sheet that floated on the surface of the nutrient solution in each tub. After 10 d (23 d from seeding), 30 uniform plants of each cultivar were transferred to their final solutions in 1.6-L polyvinylchloride pots fitted with insulated covers. Each pot contained three plants supported by foam plugs in the covers with roots completely submerged in aerated nutrient solution with N supplied as NO_3^- at either 0.2 or 3.5 m*M* as $Ca(NO_3)_2$. In addition to NO_3^-, solution composition consisted of (μM): $H_2PO_4^-$, 400; K^+, 900; Ca^{2+}, 1450 or 1800, respectively; Mg^{2+}, 600; SO_4^{2-}, 600; Cl^- 1800 or 600, respectively; Fe (Fe-DTPA; diethyleneamine pentaacetic acid), 40; BO_3^{3-}, 13; Mn, 5.0; Zn, 1.0; Cu, 0.25; and MoO_4^{2-}, 0.25. Distilled water was added to pots daily, or as needed, to replace water lost through evapotranspiration. Solution N was monitored daily and replenished with KNO_3 such that N depletion in solution did not exceed 25% of the original concentration. Solution pH was maintained between 6.0 and 6.7 with 0.1 *M* KOH or 0.5 *M* HCl, as necessary. Powdery mildew problems were controlled with weekly application of 11% fenarimol [α (2-chlorophenyl)-α-(4-chlorophenyl-5-pyrimidinemethanol] at 0.3 mL L^{-1} water applied as a hand spray. Solutions were changed following fenarimol application.

After 26 d in the final solution (49 d after seeding), plants were harvested, divided into roots and shoots, dried at 70°C for 48 h, and weighed. The dried plant material was ground to pass a 60-mesh sieve, and analyzed for total N using a modified micro-Kjeldahl digestion in conjunction with a salicyclic acid pretreatment to facilitate reduction and recovery of tissue NO_3^- (Nelson and Sommers, 1980). Total N in the digest was quantitated using an indophenol-blue colorimetric assay (Cataldo et al., 1974). Nitrogen accumulation in shoots and roots was calculated as the product of the N concentrations and weights of the respective parts. Total plant N accumulation represented the sum of shoot and root N accumulations.

Soil Experimentation

Cultivar selection and seed germination procedures were similar to those described above. To ensure successful transfer and plant establishment in soil, seedlings were grown for 23 d in one-quarter-strength Hoagland solution prior to final transplanting in plastic pots (five plants per pot) containing approximately 2786 cm^3 of a 20/80 (v/v) soil/quartz sand mix. The soil (fine-silty, mixed, mesic Typic Argiudoll; ~15.0 g kg^{-1} organic matter) in the mix was obtained from a site at the University of Illinois Ornamental Research Center used for low N studies and tested <2.2 mg NO_3^-–N kg^{-1} (2.0 *M* KCl extracts). Two times each week 200 mL of nutrient solution (pH ~ 6.0) with N supplied as NO_3^- at either 0.7 m*M* or 3.5 m*M* was applied to each pot. Solution composition at 3.5 m*M* NO_3^- was similar to that in the high N solution in the nutriculture experiment; solution composition at 0.7 m*M* NO_3^- solution was similar to that in the low N solution in the nutriculture experiment, except for Ca^{2+} which was supplied at 1700 μ*M*. Once each week, pots were flushed with 400 mL of distilled water to remove accumulating salts. After 30 d in the soil mix (60 d after seeding), plants were harvested, washed gently in distilled water to remove media from roots, and assayed for shoot and root dry weights and N concentrations as described above.

Experimental Design and Data Analysis

In both studies, the experimental design was a randomized complete block within the greenhouse bench, with a factorial arrangement of two solution N rates and six cultivars using five replications in the nutriculture experiment and six replications with soil. Nitrogen-utilization efficiency (NUE) was calculated as mg plant dry matter mg^{-1} plant N; shoot efficiency ratio (SER) as mg shoot dry matter mg^{-1} shoot N; and N-root uptake efficiency (NRE) as mg total plant N accumulated g^{-1} root dry matter. Data were subjected to a factorial analysis of variance (ANOVA) with SAS's general linear model procedure (SAS Institute, 1985). When ANOVA indicated significant treatment effects, mean separations were performed with Fischer's protected LSD at $P = 0.05$. Group-means between N-adapted and N-non-adapted cultivars were compared using single-degree-of-freedom contrasts. Correlation analysis was used to relate cultivar differences in NUE between the two experiments.

Table 1. Growth parameters in Kentucky bluegrass in nutriculture as affected by cultivar (cv) and solution NO_3^- concentration (Ns).

Cultivar (cv)†	Solution NO_3^- (Ns)	Shoot dry wt	Root dry wt	Total plant dry wt	Shoot/root dry wt
	m*M*	g			
Limousine	0.2	0.66	0.29	0.95	2.30
	3.5	1.17	0.37	1.54	3.44
		**	ns	**	*
Barzan	0.2	0.63	0.44	1.08	1.48
	3.5	1.00	0.37	1.37	2.71
		**	ns	+	***
Midnight	0.2	0.70	0.41	1.10	1.75
	3.5	1.46	0.49	1.95	2.97
		**	ns	*	***
Asset	0.2	1.45	0.99	2.44	1.45
	3.5	4.34	0.84	5.18	5.46
		***	ns	***	***
Trenton	0.2	1.04	0.63	1.67	1.67
	3.5	2.61	0.72	3.32	3.64
		***	ns	***	**
Dawn	0.2	1.28	0.84	2.12	1.53
	3.5	2.49	0.69	3.17	3.75
		**	ns	*	***
LSD 0.05 (cv × Ns)		0.42	–	0.59	0.71
Significance					
cv		***	***	***	***
Ns		***	ns	***	***
cv × Ns		***	ns	***	***
cv × Ns (non-adapted)		ns	ns	ns	ns
cv × Ns (adapted)		**	ns	**	**
Adapted vs non-adapted		***	***	***	***
(0.2 m*M* Ns)		***	***	***	**
(3.5 m*M* Ns)		***	***	***	***

*,**,***,+, ns: significant at P = 0.05, 0.01, 0.001, 0.10, non-significant, respectively.
† Non-adapted cultivars (Limousine, Barzan, Midnight); adapted cultivars (Asset, Trenton, Dawn).

Table 2. Shoot and root N concentrations in Kentucky Bluegrass in nutriculture as affected by cultivar (cv) and solution NO_3^- concentration (Ns).

Cultivar† (cv)	Solution NO_3^- (Ns)	Shoot N	Root N
	m*M*	— % dry weight —	
Limousine	0.2	4.44	2.44
	3.5	4.98	2.95
		*	*
Barzan	0.2	3.80	2.03
	3.5	4.91	3.30
		***	**
Midnight	0.2	4.48	2.63
	3.5	5.24	3.39
		**	***
Asset	0.2	3.36	1.73
	3.5	5.22	3.26
		***	***
Trenton	0.2	3.73	1.88
	3.5	5.30	3.38
		***	***
Dawn	0.2	3.27	1.77
	3.5	5.34	3.23
		***	***
LSD 0.05 (cv × Ns)		0.32	0.31
Significance			
cv		***	**
Ns		***	***
cv × Ns		***	***
cv × Ns (non-adapted)		*	*
cv × Ns (adapted)		ns	ns
Adapted vs non-adapted		***	**
(0.2 m*M* Ns)		***	***
(3.5 m*M* Ns)		ns	ns

*,**,***, ns: significant at P = 0.05, 0.01, 0.001, non-significant, respectively.
† Non-adapted cultivars (Limousine, Barzan, Midnight); adapted cultivars (Asset, Trenton, Dawn).

RESULTS AND DISCUSSION

Nutriculture Experimentation

Highly significant interactions between cultivar and solution NO_3^- supply (Ns) affected shoot dry weight, total plant dry weight, and shoot/root dry weight ratio (Table 1). These interactions mostly reflected cultivar differences in the relative response of shoot dry matter production to increasing Ns, as the rate of increase in shoot dry weight at 3.5 m*M* Ns was considerably greater in Asset and Trenton than in the other cultivars. Root dry matter production was unaffected by Ns, but was significantly higher in Asset, Trenton, and Dawn than in Limousine, Barzan, and Midnight. As a group, as well as individually, the adapted cultivars (Asset, Trenton, and Dawn) were higher yielding than the non-adapted cultivars (Limousine, Barzan, and Midnight), with mean values for total plant dry weight approximately 97% greater at 0.2 m*M* Ns, and almost 2.5-times higher at 3.5 m*M* Ns in the adapted cultivars than in the non-adapted cultivars.

Similar to the response in shoot dry weight, there was a markedly greater proportionate increase in root and shoot N concentrations with increasing Ns in the adapted cultivars than in the non-adapted cultivars (Table 2). Differences in tissue N concentrations among cultivars were more pronounced at the lower nutriculture N concentration, with highest concentrations of 4.4% shoot N and ~2.5% root N in non-adapted cultivars Limousine and Midnight. At 3.5 m*M* Ns, shoot and root N concentrations were similar among all cultivars, with an average N concentration of ~5.2% in shoots and 3.3% in roots.

Significant interactions between cultivar and N supply also affected total plant N accumulation and various N-efficiency traits, including NUE, SER, and NRE. With greater N supply, total plant N accumulation increased, while NUE and SER decreased; however, the magnitude and relative response were dependent on cultivar (Table 3). At each concentration of Ns, total N accumulation was greater in the adapted cultivars than in the non-adapted cultivars, with highest plant N levels in Asset among adapted cultivars, and in Midnight for non-adapted cultivars. The rate of increase in total N accumulation with increasing Ns averaged 1-fold in non-adapted cultivars compared to almost 2.5-fold in adapted cultivars. Meanwhile, the decline in NUE with increasing Ns was markedly greater in the adapted cultivars than in the non-adapted cultivars, ranging from a 15% reduction in Limousine to a 49% decrease in Asset. Subsequently, the relative ranking of cultivars for NUE changed depending on the level of N supply; at 0.2 m*M* Ns, NUE was highest in Asset and Dawn, while at 3.5 m*M* Ns, differences in NUE among cultivars were very much reduced, with highest NUE in Barzan and Limousine. A similar pattern developed for SER, with highest SER in Asset and Dawn at the low Ns concentration, and in Barzan and Limousine at 3.5 m*M* Ns. Averaged

Table 3. Total plant N accumulation, N-utilization efficiency (NUE), shoot efficiency ratio (SER), and N root uptake efficiency (NRE) in Kentucky bluegrass in nutriculture as affected by cultivar (cv) and solution NO_3^- concentration (Ns).

Solution NO_3^- (Ns)	Cultivar (cv)†	Plant N	NUE‡	SER‡	NRE‡
m*M*		mg			
0.2	Limousine	36.2	26.2	22.6	127.1
	Barzan	32.8	32.6	26.3	76.7
	Midnight	41.7	26.4	22.4	105.3
	Asset	61.8	40.1	30.3	66.9
	Trenton	50.7	33.2	26.9	81.6
	Dawn	56.6	37.5	30.8	67.8
	LSD 0.05	3.2	3.8	2.8	19.8
3.5	Limousine	69.1	22.2	20.1	201.4
	Barzan	62.0	22.4	20.4	166.0
	Midnight	93.6	20.9	19.2	189.3
	Asset	254.6	20.4	19.2	316.9
	Trenton	162.4	20.5	18.9	226.7
	Dawn	154.7	20.5	18.7	232.0
	LSD 0.05	30.9	1.1	0.8	49.8
LSD (0.05) cv × Ns		28.2	2.7	2.0	40.0
Significance					
cv		***	***	***	***
Ns		***	***	***	***
cv × Ns		***	***	***	***
cv × Ns (non-adapted)		ns	**	*	ns
cv × Ns (adapted)		**	+	+	*
Non-adapted vs adapted		***	***	***	**
(0.2 m*M* Ns)		***	***	***	***
(3.5 m*M* Ns)		***	***	**	***

*,**,***,+, ns: significant at $P = 0.05, 0.01, 0.001, 0.10$, non-significant, respectively.
† Non-adapted cultivars (Limousine, Barzan, Midnight); adapted cultivars (Asset, Trenton, Dawn).
‡ NUE (mg plant dry matter mg^{-1} plant N); SER (mg shoot dry matter mg^{-1} shoot N); NRE (mg plant N g^{-1} root dry matter).

over cultivars, highly significant positive relationships were found between NUE and SER at low ($r = 0.97$) and high ($r = 0.91$) levels of Ns.

In contrast to the response in both NUE and SER, NRE increased markedly in each cultivar as Ns concentration increased (Table 3). Highest NRE occurred in Limousine at 0.2 m*M* Ns and in Asset at 3.5 m*M* Ns. As a group, adapted cultivars had lower NRE at low N supply than non-adapted cultivars, while the reverse was true at 3.5 m*M* Ns. Averaged over cultivars, significant negative relationships were found between NUE and NRE at 0.2 mM Ns ($r = -0.82$) and 3.5 m*M* Ns ($r = -0.56$).

Soil Experimentation

In contrast to the nutriculture study, no significant interactions were found between cultivar and N fertilization rate for the various bluegrass growth parameters in soil, as main effects for cultivar and N rate affected shoot dry weight, root dry weight, and total dry weight (Table 4). Shoot and root dry matter production were higher in each of the adapted cultivars than in the non-adapted cultivars. As a group, the adapted cultivars produced 45% more total dry matter than non-adapted cultivars, with total dry weight highest in Asset, intermediate in Dawn, Trenton, and Limousine, and lowest in Midnight and Barzan. In each cultivar, shoot dry weight and total dry weight increased as N fertilization rate increased, while root dry weight remained relatively constant. Shoot/root dry weight ratios increased significantly in each cultivar as N supply increased, with the rate of increase in the amount of dry weight partitioned to the shoot at high N averaging 75% in non-adapted cultivars and 34% in adapted cultivars.

Table 4. Growth response in Kentucky bluegrass as affected by cultivar (cv) and N fertilization rate (Nf) in soil.

	Shoot dry wt	Root dry wt	Total dry wt	Shoot/root dry wt
	g			
Cultivar (cv)				
Limousine	1.84c‡	1.49c	3.33d	1.25a
Barzan	1.43d	1.28c	2.71e	1.16a
Midnight	1.58d	1.51c	3.09de	1.03b
Asset	2.72a	2.29a	5.01a	1.20a
Trenton	1.94bc	1.94b	3.88c	1.01b
Dawn	2.09b	2.28a	4.36b	0.92b
(non-adapted)†	1.62	1.42	3.04	1.15
(adapted)	2.25	2.17	4.42	1.04
	***	**	**	*
N rate (Nf) (m*M*)				
0.7	1.42	1.66	3.08	0.87
3.5	2.45	1.93	4.39	1.33
	***	+	***	***
Significance				
cv × Nf	ns	ns	ns	*

*,**,***,+, ns: significant at $P = 0.05, 0.01, 0.001, 0.10$, non-significant, respectively.
† Non-adapted (Limousine, Barzan, Midnight); adapted (Asset, Trenton, Dawn).
‡ Values followed by the same letter are not significantly different at $P = 0.05$.

Similar to the response in the various growth parameters, the interaction of N fertilization and cultivar for root or shoot total N concentrations was not significant (Table 5). Root and shoot N concentrations increased in each cultivar as N fertilization rate increased, with highest concentrations occurring in Barzan and Midnight. As a group, as well as individually, N concentrations in roots and shoots were higher in the non-adapted than in adapted cultivars. The one exception to these results was in Limousine, where root N levels were comparable to those in the adapted cultivars. Although N

Table 5. Shoot and root N concentrations in Kentucky bluegrass as affected by cultivar (cv) and N fertilization rate (Nf) in soil.

	Shoot N	Root N
	% dry weight	
Cultivar (cv)		
Limousine	2.32b‡	1.31b
Barzan	2.58a	1.44a
Midnight	2.44ab	1.52a
Asset	1.99d	1.31b
Trenton	2.04cd	1.25b
Dawn	2.16c	1.28b
(non-adapted)†	2.45	1.42
(adapted)	2.06	1.28
	**	**
N rate (Nf) mM		
0.7	1.75	1.19
3.5	2.76	1.52
	***	***
Significance		
cv × Nf	ns	ns

,*, ns: significant at $P = 0.01, 0.001$, non-significant, respectively.
† Non-adapted (Limousine, Barzan, Midnight); adapted (Asset, Trenton, Dawn).
‡ Values followed by the same letter are not significantly different at $P = 0.05$.

Table 6. Total plant N accumulation, N utilization efficiency (NUE), shoot efficiency ratio (SER), and N root absorption efficiency (NRE) in Kentucky bluegrass as affected by cultivar (cv) and N fertilization (Nf) rate in soil.

	Plant N	NUE§	SER§	NRE§
	mg			
Cultivar (cv)				
Limousine	64.9c‡	56.4b	45.4c	43.8a
Barzan	58.1d	51.4c	40.9d	46.5a
Midnight	64.0c	52.7c	43.7c	41.3ab
Asset	86.3a	65.7a	54.2a	37.6b
Trenton	65.8c	63.5a	52.0ab	33.9c
Dawn	76.2b	61.2a	49.3b	33.1c
(non-adapted)†	62.3	53.6	43.4	43.8
(adapted)	76.1	63.3	51.7	34.9
	*	**	*	**
N rate (Nf) (m*M*)				
0.7	43.5	70.0	58.3	26.9
3.5	94.9	45.8	36.8	51.8
	***	***	***	***
Significance				
cv × N	ns	ns	ns	**

*,**,***, ns: significant at $P = 0.05$, 0.01, 0.001, non-significant, respectively.

† Non-adapted cultivars (Limousine, Barzan, Midnight); adapted cultivars (Asset, Trenton, Dawn).

‡ Values followed by the same letter are not significantly different at $P = 0.05$.

§ NUE (mg dry matter/mg plant N); SER (mg shoot dry matter/mg shoot N); NRE (mg plant N/g root dry matter).

concentrations in both roots and shoot were noticeably lower in this study than in the nutriculture system (Table 2), at no time did any cultivars show signs of N deficiency. The concentrations of shoot N in this experiment were comparable, or slightly higher, than those reported for several cultivars of Kentucky bluegrass grown under comparable greenhouse conditions (Wesely et al., 1985).

In each cultivar, total plant N accumulation increased with increased N fertilization rate (Table 6). As a group, adapted cultivars accumulated significantly more N than non-adapted cultivars, with total N levels highest in Asset, followed by Dawn, intermediate in Trenton, Midnight, and Limousine, and lowest in Barzan. Similarly, both NUE and SER were higher in the adapted cultivars than in nonadapted cultivars; however, the reverse was true with NRE. With increased N fertilization rate, both NUE and SER decreased while NRE increased. Differences among cultivars in NUE were not as great as in the nutriculture experiment; under low N supply, NUE ranged from 63.6 in Midnight to 77.4 in Asset. Similar to the nutriculture system, there was a highly significant positive relationship ($r = 0.95$) between NUE and SER (data averaged over cultivars and Ns).

Correlation between NUE in nutriculture and soil showed that despite marked effects of N supply on NUE there was a fairly high degree of consistency ($r = 0.88$) in cultivar response for NUE between the two experiments (Fig. 1). With high N supply, variability in cultivar differences in NUE between the two experiments was small, particularly in the adapted cultivars. At low N supply, there appeared to be more genotypic variation in NUE between the two experiments; however, relative ranking of genotypes for NUE were comparable in nutriculture and soil.

These studies show significant genotypic variation in various N-efficiency traits in six bluegrass cultivars, with the magnitude and relative response of the cultivars greatly affected by the level of N supply, and closely aligned with cultivar type. The results are consistent with previous work where typically higher NUE is reported at lower rates of N supply (Anderson et al., 1984; Gascho et al., 1986). The higher NUE values in soil than in nutriculture were attributed to greater root growth in soil, as differences in root dry weights were the major contributing factors to total dry weight differences between the two experiments.

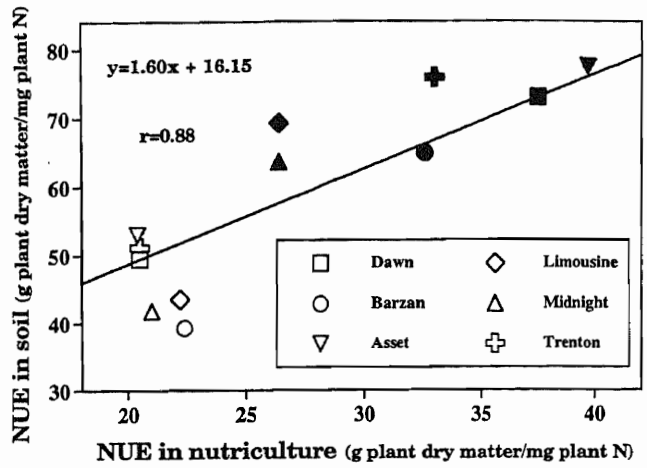

Fig. 1. Relationship between N-utilization efficiency (NUE) in six Kentucky bluegrass cultivars at low (shaded symbols) and high (open symbols) levels of N supply in nutriculture and soil. Low N was supplied at 0.2 and 0.7 m*M* NO_3^- in nutriculture and soil, respectively; high N was supplied at 3.5 m*M* NO_3^-.

As a group, as well as individually, adapted cultivars (Asset, Dawn, and Trenton) were higher yielding, more responsive to increasing solution N concentration, and more efficient (dry matter produced per unit of plant N) at low levels of N supply than non-adapted cultivars (Limousine, Barzan, or Midnight). Whiteaker et al. (1976) classified genotypic response to fertilizer input into three categories: inefficient-responders, those that perform poorly at low nutrient levels yet very well at high levels; efficient-non-responders, those that perform well at low nutrient levels and poorly at high levels; and efficient-responders, those that grow well at low and high levels. The high NUE values in Asset at low N supply, in combination with high dry weight at high N supply (3.5 m*M*), in both nutriculture and soil identified this cultivar as an efficient-responder, well adapted over a wide range of environmental and nutritional conditions. In contrast, nonadapted cultivars were generally "inefficient-non-responders" (our terminology) because of low NUE at low N supply and a relatively modest increase in dry matter production at high N.

Differences in NUE among cultivars were more associated with shoot efficiency (shoot dry matter produced per unit of shoot N) than root absorption efficiency (mg total plant N per g root dry weight), as the relative ranking of cultivars for NRE differed markedly from that for NUE, while the relative rankings (as well as correlations) for SER and NUE corresponded closely to each other. From a practical point of view, SER may

be a more important trait than NUE because clippings can be easily obtained from cultivars several times during the growing season without damaging plants. Vigorous shoot growth at low plant N levels would be desirable in high maintenance situations since mowing of turf containing less N in its leaves would result in less nutrient removal from plants. Cultivars, such as Asset and Trenton, that exhibit high SER would appear to be well suited to golf courses, home lawns, and many athletic fields. Although these results were based on a limited number of genotypes, differences between cultivars in several of the physiological parameters associated with N uptake and efficiency appeared sufficiently broad to suggest the potential for genetic improvement for NUE in Kentucky bluegrass.

We acknowledge that field environments may vary considerably, which could cause potential differences in N uptake. However, despite noticeably higher NUE in soil than in nutriculture and significant effects of N fertilization rates, genotypic differences in the various N-efficiency traits found among six bluegrass cultivars in solution culture were also apparent when the cultivars were grown in the soil/sand mix. While the similarities of the actual N conditions between nutriculture and soil remain in question, it appears that solution culture can be used as an effective surrogate of characterizing NUE in divergent types of bluegrass cultivars.

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