The Relationship Between Applied Nitrogen, Nitrogen Concentration in Herbage and Seed Yield in Perennial Ryegrass (*Lolium perenne* L.). II. Cultivars in Oregon.

W.C. Young III[1], T.B. Silberstein[1], T.G. Chastain[1] and J.S. Rowarth[2]

ABSTRACT

The objective of this research was to verify if critical concentrations or contents of nitrogen (N) necessary for optimum perennial ryegrass (*Lolium perenne* L.) seed production could be identified fourteen days after early spring N application in Oregon, and, if so, whether the critical thresholds differed among cultivars and stand age. Cvs. Grasslands Nui, Linn and Buccaneer were drilled in 1995 and 1996, and harvested in two subsequent years. Nitrogen was applied in various combinations of rates (0-200 kg ha^{-1})and timing (autumn, late winter and early spring) to create a range of herbage N concentration in spring. Dry matter and N concentration were analysed 14 days after application of N in early spring. Seed yield and thousand seed weight were analysed at harvest. Seed yield was affected by year, stand age and cultivar. Despite this, the relationship between herbage N concentration 14 days after N was applied in early spring and seed yield indicated that a herbage N concentration of over 3 % was required for a seed yield of over 1100 kg ha^{-1}. Furthermore, for 80 % relative seed yield (calculated relative to the maximum seed yield for each cultivar in each year) an N content of 76 kg ha^{-1} was required in early spring ($r = 0.85$). Both relationships were independent of year, cultivar and stand age.

Additional index words: herbage nitrogen content, spikelet initiation, thousand seed weight, seed yield variability.

INTRODUCTION

Perennial ryegrass seed crops occupy 63000 ha in Oregon, contributing over half of global ryegrass production. Fertiliser nitrogen (N) is commonly applied in spring as nitrogen is the most critical element affecting seed yield of perennial ryegrass in Oregon (Youngberg, 1980) and residual nitrogen in the soil is negligible in spring due to wet winters (Horneck, Hart and Young, 1992).

Grass seed growers in western Oregon have historically applied 30 % more N than recommended (Horneck and Hart, 1988). Recent research has concentrated on finding the balance between applied N, seed yield and lodging, recognising the need to improve N fertiliser management for greater N-use efficiency whilst safeguarding the environment (Young, Chilcote and Youngberg, 1995; Young, Youngberg, Chilcote and Hart, 1997). Response in seed yield to spring applied N is cultivar dependent, and is unlikely at rates greater than 96 kg ha^{-1} (plus 30- 50 kg ha^{-1} in autumn) for older forage-type perennial ryegrasses or 130 kg ha^{-1} (plus 30- 50 kg ha^{-1} in autumn) for turf-type perennial ryegrasses. Newer cultivars may respond to 170 kg ha^{-1} (plus autumn N) and, as this was the maximum amount of N applied, further responses were possible. Results from time and amount of N experiments are, however, temporally and spatially specific (Rowarth, 1997). Research on identifying an indicator of nitrogen status related to seed yield has revealed that herbage N concentration measured 14 days after spikelet initiation (when the bulk of N is traditionally applied (Hampton, 1987)) is related to seed yield (Rowarth and Archie, 1994; 1995). However, this research was done on only one cultivar, Grasslands Nui, and only under New Zealand conditions. Further investigation (Rowarth, Boelt, Hampton, Marshall, Rolston, Sicard, Silberstein, Sedcole and Young, 1998) has indicated that N content in early spring may be a more useful predictive tool than herbage N concentration, as it overcomes differences caused by soil temperature.

The objective of this research was to verify if critical concentrations or contents of nitrogen necessary for optimum seed production could be identified fourteen days after early spring nitrogen application in Oregon, and, if so, whether the critical thresholds differed between cultivars and stand age.

MATERIALS AND METHODS

Perennial ryegrass cvs. Grasslands Nui, Linn and Buccaneer were drilled at Hyslop Farm, Corvallis (44° 35' N), Oregon, in the autumn of 1995 and 1996, using standard carbon seeding planting. All cultural practices (fungicides and herbicides) were used in accordance with registered products and recommended rates; pesticides were applied prophylactically in both years. The trials were not irrigated. Seed was harvested for two years from each sowing, i.e., the 1995 sowing was harvested in 1996 and 1997; the 1996 sowing was harvested in 1997 and 1998.

Nitrogen treatments were applied as indicated (Table 1). Timing of the three nitrogen applications was: late autumn after regrowth (or establishment), late winter (approximately double-ridge) and early spring (internode elongation). Plots were 2.4 m by 0.9 m wide in 1995 and 2.4 m by 1.8 m in 1996.

Fourteen days after the early spring application of nitrogen, the herbage was cut just above the leaf sheath from a known area. Herbage was dried overnight at approximately 65 °C, and dry weight recorded, before being sent to New Zealand for analysis (Basson, 1976). Seed was harvested when seed moisture was 40-42 %. After air drying, threshing and cleaning, seed yield and thousand seed weight (TSW) were recorded.

Nitrogen content was calculated from dry matter yield and herbage N concentration 14 days after early spring nitrogen application. Apparent nitrogen recovery (ANR; %) and nitrogen use efficiency (NUE; kg extra seed per kg applied N)

[1] *Department of Crop and Soil Science, Crop Science Building 107, Oregon State University, Corvallis, OR 97331-3002, USA*
[2] *Soil, Plant and Ecological Sciences Division, PO Box 84, Lincoln University, Canterbury, New Zealand.*
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Nitrogen content was calculated from dry matter yield and herbage N concentration 14 days after early spring nitrogen application. Apparent nitrogen recovery (ANR; %) and nitrogen use efficiency (NUE; kg extra seed per kg applied N) were calculated as described by Rowarth *et al.* (1998). Relative seed yield was calculated for each cultivar in each year relative to the maximum seed yield for that cultivar in that year.

Analysis of variance and regression analysis were performed using Minitab. The Cate-Nelson separation technique, which involves partitioning data into diagonally opposite quadrats, was used to establish critical thresholds for response; the more complete the separation, the better the indication of a threshold (Cate and Nelson, 1965).

RESULTS AND DISCUSSION

Seed yield, thousand seed weight, herbage nitrogen, dry matter yield, nitrogen content, apparent nitrogen recovery and nitrogen use efficiency data for cv. Grasslands Nui have been presented and discussed in Rowarth *et al.* (1998). Trends for cvs. Linn and Buccaneer were similar. There were no significant effects of nitrogen on seed yield for either cultivar in 1996 (Table 1). Maximum seed yields were 1184 and 855 kg ha^{-1} for cvs. Linn and Buccaneer, respectively, in comparison with 1734 kg ha^{-1} for cv. Grasslands Nui. Seed yields without any nitrogen were 74 and 61 % of maximum

Table 1. Effect of applied nitrogen on seed yield, thousand seed weight, herbage nitrogen, dry matter yield, nitrogen content, apparent nitrogen recovery and nitrogen use efficiency for first year crops in 1996 of (a) cv. Linn and (b) cv. Buccaneer. (Data for cv. Grasslands Nui have been presented in Rowarth *et al.*, 1998.)

(a) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	873	2.28	1.73	2389	41	-	-
00-50-00	50	843	2.39	1.78	4074	72	62.9	-
30-50-00	80	876	2.28	1.79	4065	73	39.8	0.04
00-00-50	50	910	2.38	2.53	3257	81	83.9	0.74
00-50-50	100	888	2.36	2.69	4725	127	84.9	0.15
30-50-50	130	1110	2.35	2.45	4790	116	56.6	1.82
30-00-70	100	1167	2.33	2.67	3871	100	62.6	2.94
30-50-70	150	1112	2.49	2.89	5270	152	74.4	1.59
30-50-90	170	1184	2.44	2.95	4214	123	48.5	1.83
50-70-80	200	1177	2.47	3.10	4282	132	45.9	1.52
LSD P<0.05		ns	0.11	0.40	1078	27.0	na[6]	na
(b) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	520	1.69	1.68	1854	32	-	-
00-50-00	50	681	1.69	1.95	3160	62	61.0	3.22
30-50-00	80	671	1.70	1.86	3515	65	41.5	1.89
00-00-50	50	546	1.71	2.79	2635	74	81.2	0.52
00-50-50	100	855	1.66	2.86	3308	94	62.5	3.35
30-50-50	130	681	1.74	2.78	3718	103	54.6	1.24
30-00-70	100	680	1.68	3.17	2782	88	56.8	1.60
30-50-70	150	779	1.73	3.31	3871	128	64.8	1.73
30-50-90	170	608	1.72	3.56	4219	150	69.2	0.52
50-70-80	200	786	1.71	3.22	4610	148	58.1	1.33
LSD P<0.05		ns	ns	0.24	773	24	na[6]	na

[1] *Timing of the three nitrogen applications was: late autumn after regrowth (or establishment), late winter (approximately double-ridge) and early spring (internode elongation).*
[2] *Analysed 14 days after early spring nitrogen application*
[3] *DMY x N% 14 days after early spring nitrogen application*
[4] *Apparent nitrogen recovery:*
[5] *Nitrogen use efficiency:*
[6] *Not available as calculated from means*

Table 2. Effect of applied nitrogen on seed yield, thousand seed weight, herbage nitrogen, dry matter yield, nitrogen content, apparent nitrogen recovery and nitrogen use efficiency for first year crops in 1997 of (a) cv. Linn and (b) cv. Buccaneer. (Data for cv. Grasslands Nui have been presented in Rowarth *et al*, 1998.)

(a) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	593	2.10	1.81	557	10	-	-
00-50-00	50	1114	2.30	3.09	1535	47	74	10.42
30-50-00	80	1014	2.27	2.51	1922	48	48	5.26
00-00-50	50	864	2.38	3.63	738	26	32	5.42
00-50-50	100	1641	2.40	4.07	1840	75	65	10.48
30-50-50	130	1330	2.42	3.46	2491	86	58	5.66
30-00-70	100	1184	2.41	3.48	1899	66	56	5.91
30-50-70	150	1328	2.42	3.73	2226	82	48	4.90
30-50-90	170	1360	2.48	4.43	2211	98	52	4.51
50-70-80	200	1170	2.51	4.04	2176	86	38	2.89
LSD P<0.05		343	0.10	0.77	490	18		

(b) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	485	1.78	2.17	325	7	-	-
00-50-00	50	1184	1.80	2.99	1044	30	46	13.98
30-50-00	80	1258	1.80	2.84	1943	55	60	9.66
00-00-50	50	1132	1.86	4.02	592	23	32	12.94
00-50-50	100	1527	1.87	4.21	1436	60	53	10.42
30-50-50	130	1733	1.87	3.98	1817	72	50	9.60
30-00-70	100	1353	1.92	3.70	1647	61	54	8.68
30-50-70	150	1825	1.90	4.27	1917	81	49	8.93
30-50-90	170	1860	2.00	4.33	2121	91	49	8.09
50-70-80	200	1969	2.00	4.21	2296	96	45	7.42
LSD P<0.05		263	0.10	0.41	423	13		

[1] *Timing of the three nitrogen applications was autumn, late winter and early spring (see Table 1)*
[2] *Analysed 14 days after early spring nitrogen application*
[3] *DMY x N% 14 days after early spring nitrogen application*
[4] *Apparent nitrogen recovery*
[5] *Nitrogen use efficiency*

seed yields for cvs Linn and Buccaneer, respectively, while that for cv. Grasslands Nui was 65 % (Rowarth *et al.*, 1998); this small response to applied N is thought to reflect infestation with rust in cvs Linn and Buccaneer, which was severe, despite applications of propiconazole.

Thousand seed weight (TSW) tended to increase with increasing applied N; this effect was significant (P<0.05) in cv. Linn. Herbage N increased significantly (P<0.05) with increasing applied N, particularly when applied in spring, and dry matter yield was increased significantly (P<0.05), particularly when N was applied in late winter (Table 1). N content was significantly (P<0.05) and positively affected by increasing applied N, reflecting trends seen in both herbage N concentration and dry matter yield. N applied in autumn was not efficiently recovered by plants (as calculated by ANR) (Table 1), which may reflect waterlogged conditions (which enhance denitrification losses) during December and February. On average, 62 % of winter nitrogen and 83 % of spring nitrogen was recovered by the plants, in comparison with only 40 % of autumn nitrogen. Nitrogen use efficiency (NUE) was greatest for the 30-00-70 treatment for cv. Linn and the 00-50-00 and 00-50-50 treatments for cv. Buccaneer (Table 1), but was low in comparison with other reported data (Rowarth *et al.*, 1998; Sicard and Rowarth, 1998), confirming the suggestion that some factor other than nitrogen was limiting yields.

Maximum seed yields from first year seed crops in 1997 were greater than for 1996 (Table 2). Responses to applied nitrogen were significant (P<0.05) and maximum yields were achieved with 100 kg ha^{-1} N (00-50-50) in cv. Linn and 200 kg ha^{-1} N (50-70-80) in cv. Buccaneer. In cv. Linn, the maximum yield also had the greatest NUE, whereas in cv. Buccaneer the greatest NUE was with the 00-50-00 treatment (Table 2). All NUEs were markedly higher than in the previous year. Increasing applied N had a significant and positive effect on TSW, herbage N concentration and dry matter yield (Table 2). Trends were similar to the previous year in that herbage N concentration increased in

Table 3. Effect of applied nitrogen on seed yield, thousand seed weight, herbage nitrogen, dry matter yield, nitrogen content, apparent nitrogen recovery and nitrogen use efficiency for second year crops in 1997 of (a) cv. Linn and (b) cv. Buccaneer. (Data for cv. Grasslands Nui have been presented in Rowarth *et al.*, 1998.)

(a) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	454	2.18	1.17	2415	29	-	-
00-50-00	50	842	2.40	1.83	3069	56	54	7.76
30-50-00	80	888	2.37	1.80	4034	73	55	5.43
00-00-50	50	773	2.41	2.23	2585	57	56	6.38
00-50-50	100	1099	2.39	2.66	3614	95	66	6.45
30-50-50	130	1030	2.30	2.45	4797	118	68	4.43
30-00-70	100	1376	2.44	2.25	3268	72	43	9.22
30-50-70	150	1022	2.33	2.86	4709	135	71	3.79
30-50-90	170	898	2.31	3.01	4679	140	65	2.61
50-70-80	200	1065	2.20	2.73	5824	158	65	3.06
LSD P<0.05		397	0.15	0.29	1326	29		

(b) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	303	1.63	1.41	1251	17	-	-
00-50-00	50	916	1.70	2.01	2139	43	52	12.26
30-50-00	80	1199	1.72	1.04	2983	61	55	11.20
00-00-50	50	799	1.85	2.81	1308	36	38	9.92
00-50-50	100	1360	1.78	3.55	2118	76	57	10.57
30-50-50	130	1283	1.83	3.23	2857	93	58	7.54
30-00-70	100	1247	1.73	3.02	2463	75	58	9.44
30-50-70	150	1362	1.78	3.24	3338	109	61	7.06
30-50-90	170	1631	1.91	3.71	3716	138	71	7.81
50-70-80	200	1665	1.85	3.74	3938	146	65	6.81
LSD P<0.05		326	0.11	0.35	890	30		

[1] *Timing of the three nitrogen applications was autumn, late winter and early spring (see Table 1)*
[2] *Analysed 14 days after early spring nitrogen application*
[3] *DMY x N% 14 days after early spring nitrogen application*
[4] *Apparent nitrogen recovery*
[5] *Nitrogen use efficiency*

particular with spring N whereas dry matter increased in particular with winter N. However, in general, herbage N concentration was greater than in 1996 and dry matter yield was reduced. Nitrogen content was generally less than the previous year, but ANRs were greater. This apparent anomaly reflects the small N content in the zero N plots in 1997 *cf* 1996; the latter was due to high available N in the soil as the ryegrass crop followed lupins. ANR was reduced for N applied in spring, in comparison with the previous year. ANR of winter N for cv. Linn was higher than the previous year, but for cv. Buccaneer was lower; the reverse was seen for the autumn N. These differences reflect changes in dry matter yield, and support the suggestion that the major determinant of nitrogen uptake is leaf expansion (Grindlay, 1997).

Second year crops in 1997 had lower yields (Table 3) than first year crops (Table 2). The maximum yield in cv. Linn was 1376 kg ha^{-1} and was achieved with 30-00-70; this treatment also gave the highest NUE (Table 3). In cv. Buccaneer the maximum yield of 1665 kg ha^{-1} was achieved with the 50-70-80 treatment, but NUE was only 56 % that of the 00-50-00 treatment. However, the 00-50-00 treatment gave only 55 % of the maximum yield. Thousand seed weight, herbage N concentration and dry matter yield were all significantly affected by increasing N, the trends being the same as for the first year crop. Overall, dry matter yield was greater for the second (Table 3) than the first (Table 2) year crops, and hence N content was higher. ANR was also increased. Although there was little difference in ANR between seasons, ANR did tend to increase where nitrogen was applied to increase (autumn and winter by increasing dry matter) and fulfil (winter and spring, by increasing concentration) nitrogen demand (Rowarth, 1997).

Second year crops in 1998 (Table 4) had lower yields than second year crops in 1997 (Table 3). Maximum yield in cv. Linn was 1229 kg ha^{-1}, achieved with the 30-50-90 treatment;

maximum yield in cv. Buccaneer was 1337 kg ha^{-1} which was achieved with the 50-70-90 treatment. In neither case did these treatments have the highest NUE; in cv. Buccaneer, however, the maximum seed yield was not significantly different from the treatment which did have the highest NUE (30-00-70). TSW, herbage N concentration and DMY all increased with increasing applied N, as did N content (Table 4). ANR was low for winter-applied or spring-applied N, but was improved when either were applied in conjunction with autumn N.

Regressions fitted to the individual responses indicated that applied N accounted for 0.25-0.92 % of the variability in seed yield (Table 5). Relationships were significant where sites were responsive to N (generally indicated by a 'b' factor of greater than 3 (where Y= a + bX)) (Table 5). Responsiveness was more affected by year than cultivar or age of crop. Combining the data shows that for 80 % relative seed yield, regardless of year or crop, at least 100 kg ha^{-1} N should be applied (Fig. 1); the correlation (r = 0.82) suggests that following this recommendation will achieve the correct result (relative seed yield >80 %) 4 out of 5 times. A similar requirement for 100 kg ha^{-1} N has been reported for cv. Grasslands Nui (Rowarth *et al.*, 1998). This relationship suggests that, for seed yield, amount of N is more critical than timing (within the range of treatments examined). It does not, however, consider the environmental impact of applied N (leaching and volatilisation), ANR or NUE, all of which are becoming increasingly important in legislation underpinning sustainable management practices.

Regression analysis for dry matter and applied N showed that there was a significant relationship in 11 out of the 12 experiments (Table 6). On average (excluding the non-significant response) 73 % of the variability in dry matter was accounted for by applied N (range R^2 = 0.45 - 0.88). Seed yield and dry matter yield were, however, significantly related in only seven of the experiments (Table 7). This provides further

Table 4. Effect of applied nitrogen on seed yield, thousand seed weight, herbage nitrogen, dry matter yield, nitrogen content, apparent nitrogen recovery and nitrogen use efficiency for second year crops in 1998 of (a) cv. Linn and (b) cv. Buccaneer. (Data for cv. Grasslands Nui have been presented in Rowarth *et al.*, 1998.)

(a) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	329	2.08	1.04	2156	22	-	-
00-50-00	50	614	2.18	1.32	3120	41	38	5.70
30-50-00	80	995	2.24	1.41	4660	66	55	8.33
00-00-50	50	844	2.31	2.04	2181	44	44	10.30
00-50-50	100	1091	2.38	2.01	3410	69	47	7.62
30-50-50	130	991	2.32	2.15	5258	113	70	5.09
30-00-70	100	1124	2.39	1.86	4493	84	62	7.95
30-50-70	150	1078	2.36	2.45	4009	98	51	4.99
30-50-90	170	1229	2.43	2.46	4212	104	48	5.29
50-70-80	200	1136	2.39	2.97	4678	139	59	4.04
LSD P<0.05		308	0.13	na	1173			

(b) Nitrogen treatment[1] (kg ha^{-1})	Total N (kg ha^{-1})	Seed yield (kg ha^{-1})	TSW (g)	Herbage N[2] %	DMY[3] (kg ha^{-1})	N content[3] (kg ha^{-1})	ANR[4] (%)	NUE[5]
00-00-00	00	313	1.72	1.10	2196	24	-	-
00-50-00	50	576	1.81	1.43	2960	42	36	5.26
30-50-00	80	785	1.83	1.36	4387	60	45	5.90
00-00-50	50	693	1.90	1.80	2595	47	46	7.60
00-50-50	100	1032	1.94	2.12	3808	81	57	7.19
30-50-50	130	1263	1.89	2.45	4443	109	65	7.31
30-00-70	100	1201	1.94	2.35	4001	94	70	8.88
30-50-70	150	1100	1.96	2.29	4967	114	60	5.25
30-50-90	170	1324	2.04	2.52	4660	117	55	5.95
50-70-80	200	1337	2.06	1.97	5604	110	43	5.12
LSD P<0.05		280	0.10	na	982			

[1] *Timing of the three nitrogen applications was autumn, late winter and early spring (see Table 1)*
[2] *Analysed 14 days after early spring nitrogen application*
[3] *DMY x N% 14 days after early spring nitrogen application*
[4] *Apparent nitrogen recovery*
[5] *Nitrogen use efficiency*

Table 5. Regression relationships between seed yield (kg ha⁻¹) and nitrogen applied (kg ha⁻¹).

Year	Stand age	Cultivar	Regression equation	R^2	P
1996	1st year	Nui	Seed yield = 1190 + 2.94 N	0.70	0.001
		Linn	Seed yield = 810 + 1.98 N	0.65	0.01
		Buccaneer	Seed yield = 578 + 0.99 N	0.25	ns
1997	1st year	Nui	Seed yield = 780 + 5.84 N	0.80	0.001
		Linn	Seed yield = 837 + 3.13 N	0.36	0.05
		Buccaneer	Seed yield = 704 + 7.08 N	0.92	0.001
1997	2nd year	Nui	Seed yield = 583 + 1.78 N	0.26	ns
		Linn	Seed yield = 702 + 2.35 N	0.28	ns
		Buccaneer	Seed yield = 527 + 6.31 N	0.88	0.001
1998	2nd year	Nui	Seed yield = 609 + 2.49 N	0.49	0.02
		Linn	Seed yield = 547 + 3.85 N	0.68	0.001
		Buccaneer	Seed yield = 411 + 5.35 N	0.85	0.001

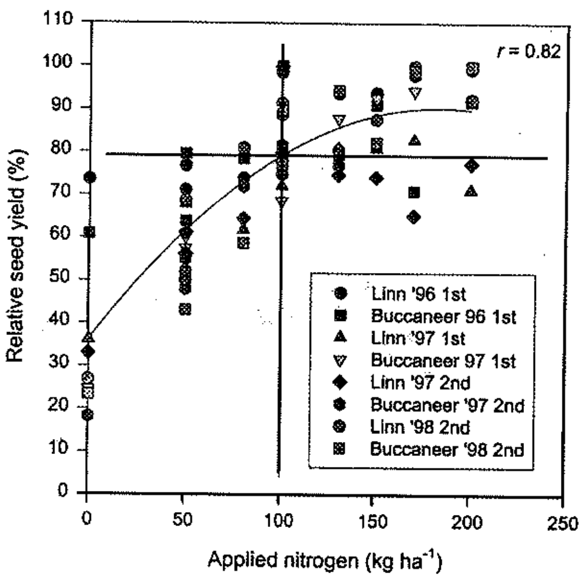

Fig. 1. Effect of applied nitrogen (kg ha⁻¹) on perennial ryegrass seed yield relative to the maximum yield for each trial. Cate Nelson separation technique (Cate and Nelson, 1965) is used to show a critical threshold. (Data for cv. Grasslands Nui are presented in Rowarth *et al.*, 1998.)

evidence for the suggestion of a limiting factor, e.g., disease, as under ideal conditions seed yield and dry matter have been found to be closely related (Rowarth, unpubl.).

Applied N accounted for more than half (R^2 = 0.50-0.86; average 0.69) of the variability in herbage N concentration (Table 8). Year had a large effect on herbage N concentration without fertiliser, but the response factor was similar for all experiments (range 0.007-0.011; average 0.0088). For cv. Linn the response factor was 0.0085 and for cv. Buccaneer it was 0.009; this is similar for the response factor derived for cv. Grasslands Nui (0.009) (Rowarth *et al.*, 1998) and indicates that 50 kg ha⁻¹ N applied at node elongation will change the herbage N concentration of cv. Linn by 0.43 % and of cv. Buccaneer by 0.45 % (*cf.* Grasslands Nui by 0.45 %). If herbage N concentration is to be adjusted after node elongation, it is likely that slightly more N will be required as the ryegrass will be less efficient, physiologically, at assimilating it (Scholefield, 1993) and there is likely to be more competition from the soil microbial biomass.

Seed yield was significantly related to herbage N concentration in 10 of the 12 experiments, accounting for 32-78 % (average R^2 = 0.56) of the variability (Table 9). The response factors were not affected by cultivar, age of crop or year. Combining all data indicated that for a seed yield of over 1100 kg ha⁻¹, an herbage N concentration of over 3 % is required in early spring; the correlation (r = 0.71) suggests that following this recommendation will achieve the correct result (seed yield >1200 kg ha⁻¹) 2 out of 3 times (Fig 2). The correlation between herbage N concentration (%) and relative seed yield was only 0.58, and no threshold was apparent (data not presented).

Examination of the relationship between nitrogen content 14 days after early spring nitrogen application and seed yield revealed a significant relationship in nine of the 12 experiments (Table 10). On average (excluding the non-significant experiments) 71 % of the variability in seed yield was accounted for by a change in nitrogen content (range 0.38-0.93). Combining all data indicated that for a relative seed yield of 80 %, herbage N content should be 78 kg ha⁻¹ in early spring (Fig. 3), which compares well with recommendations for cv. Grasslands Nui (70 kg ha⁻¹) (Rowarth *et al.*, 1998). Including the cv. Grasslands Nui data (Fig 4.) did not change the relationship identified for cvs Linn and Buccaneer, suggesting the relationship is independent of cultivar, year, stand age and climate.

CONCLUSIONS

Standard analysis of the effect of N on seed yield showed that significant responses to N were unlikely above a total of 100 kg ha⁻¹ in cv. Linn and 130 kg ha⁻¹ in cv. Buccaneer, thus supporting the conclusions of Young *et al.* (1995; 1997). The lack of response is thought to be due to disease pressure. NUE at 100 kg ha⁻¹ was, in most cases, high; whether the 00-50-50 or 30-00-70 treatment gave the highest NUE depended upon year, probably reflecting soil temperatures when the N was applied.

Regression analysis, in combination with a separation

Table 6. Regression relationships between dry matter at stem elongation (kg ha^{-1}) and nitrogen applied (kg ha^{-1}).

Year	Stand age	Cultivar	Regression equation	R^2	P
1996	1st year	Nui	Dry matter = 2570 + 11.6 N	0.58	0.01
		Linn	Dry matter = 3111 + 9.6 N	0.45	0.02
		Buccaneer	Dry matter = 2096 + 12.3 N	0.86	0.001
1997	1st year	Nui	Dry matter = 879 + 9.5 N	0.67	0.01
		Linn	Dry matter = 847 + 8.9 N	0.67	0.01
		Buccaneer	Dry matter = 503 + 9.8 N	0.80	0.001
1997	2nd year	Nui	Dry matter = 2560 + 12.7 N	0.74	0.001
		Linn	Dry matter = 2160 + 16.9 N	0.86	0.001
		Buccaneer	Dry matter = 1167 + 14.0 N	0.83	0.001
1998	2nd year	Nui	Dry matter = 3747 + 19.9 N	0.69	0.001
		Linn	Dry matter = 3084 + 4.2 N	0.00	ns
		Buccaneer	Dry matter = 2233 + 16.8 N	0.88	0.001

Table 7. Regression relationships between seed yield (kg ha^{-1}) and dry matter yield (kg ha^{-1}).

Year	Stand age	Cultivar	Regression equation	R^2	P
1996	1st year	Nui	Seed yield = 772 + 0.204 DMY[1]	0.75	0.001
		Linn	Seed yield = 703 + 0.076 DMY	0.08	ns
		Buccaneer	Seed yield = 424 + 0.076 DMY	0.02	ns
1997	1st year	Nui	Seed yield = 489 + 0.482 DMY	0.67	0.01
		Linn	Seed yield = 541 + 0.352 DMY	0.56	0.01
		Buccaneer	Seed yield = 524 + 0.600 DMY	0.75	0.001
1997	2nd year	Nui	Seed yield = 357 + 0.106 DMY	0.16	ns
		Linn	Seed yield = 569 + 0.096 DMY	0.09	ns
		Buccaneer	Seed yield = 158 + 0.390 DMY	0.76	0.001
1998	2nd year	Nui	Seed yield = 308 + 0.096 DMY	0.38	0.05
		Linn	Seed yield = 593 + 0.099 DMY	0.09	ns
		Buccaneer	Seed yield = - 148 + 0.28 DMY	0.72	0.001

[1] *Dry matter yield*

Table 8. Regression relationships between concentration of nitrogen in herbage (%) and nitrogen applied (kg ha^{-1}).

Year	Stand age	Cultivar	Regression equation	R^2	P
1996	1st year	Nui	Herbage N % = 1.72 + 0.008 N	0.77	0.001
		Linn	Herbage N % = 1.73 + 0.007 N	0.66	0.01
		Buccaneer	Herbage N % = 1.81 + 0.009 N	0.62	0.01
1997	1st year	Nui	Herbage N % = 2.40 + 0.010 N	0.59	0.01
		Linn	Herbage N % = 2.40 + 0.010 N	0.56	0.01
		Buccaneer	Herbage N % = 2.68 + 0.010 N	0.57	0.01
1997	2nd year	Nui	Herbage N % = 1.41 + 0.010 N	0.86	0.001
		Linn	Herbage N % = 1.46 + 0.008 N	0.75	0.001
		Buccaneer	Herbage N % = 1.70 + 0.011 N	0.73	0.001
1998	2nd year	Nui	Herbage N % = 0.94 + 0.007 N	0.80	0.001
		Linn	Herbage N % = 1.06 + 0.009 N	0.82	0.001
		Buccaneer	Herbage N % = 1.31 + 0.006 N	0.50	0.02

Table 9. Regressions relationships between seed yield (kg ha^{-1}) and concentration of nitrogen in herbage (%)[1].

Year	Stand age	Cultivar	Regression equation	R^2	P
1996	1st year	Nui	Seed yield = 764 + 288 N%	0.50	0.02
		Linn	Seed yield = 460 + 225 N%	0.58	0.01
		Buccaneer	Seed yield = 515 + 61 N%	0.04	ns
1997	1st year	Nui	Seed yield = 9 + 399 N%	0.56	0.01
		Linn	Seed yield = 176 + 287 N%	0.55	0.01
		Buccaneer	Seed yield = - 462 + 516 N %	0.70	0.001
1997	2nd year	Nui	Seed yield = 327 + 180 N%	0.33	0.05
		Linn	Seed yield = 351 + 258 N%	0.29	ns
		Buccaneer	Seed yield = - 94 + 442 N%	0.72	0.001
1998	2nd year	Nui	Seed yield = 412 + 273 N%	0.32	0.05
		Linn	Seed yield = 223 + 366 N%	0.55	0.01
		Buccaneer	Seed yield = - 262+ 632 N%	0.78	0.001

[1] *Samples taken 14 days after early spring nitrogen application.*

Table 10. Regressions relationships between seed yield (kg ha^{-1}) and nitrogen content (kg ha^{-1})[1].

Year	Stand age	Cultivar	Regression equation	R^2	P
1996	1st year	Nui	Seed yield = 956 + 5.5 N content	0.84	0.001
		Linn	Seed yield = 714 + 3.0 N content	0.41	0.05
		Buccaneer	Seed yield = 555 + 1.3 N content	0.14	ns
1997	1st year	Nui	Seed yield = 591 + 12.0 N content	0.83	0.001
		Linn	Seed yield = 623 + 8.6 N content	0.69	0.001
		Buccaneer	Seed yield = 600 + 14.5 N content	0.90	0.001
1997	2nd year	Nui	Seed yield = 543 + 2.3 N content	0.18	ns
		Linn	Seed yield = 690 + 2.7 N content	0.14	ns
		Buccaneer	Seed yield = 474 + 8.9 N content	0.84	0.001
1998	2nd year	Nui	Seed yield = 574 + 2.9 N content	0.38	0.05
		Linn	Seed yield = 469 + 6.1 N content	0.59	0.01
		Buccaneer	Seed yield = 167 + 10.0 N content	0.93	0.001

[1] *N % x DM. Samples taken 14 days after early spring nitrogen application.*

technique, established a critical threshold for N content (14 days after N application at node elongation) and relative seed yield. The threshold was similar to that established for cv. Grasslands Nui (Rowarth *et al.*, 1998), which suggests that this relationship is relatively independent of year, cultivar and management system.

Using the critical thresholds for yield based on N content, advisers can make recommendations to growers based on the individual requirements for their crops. Combined with information on how much N is required to adjust the herbage N concentration, plus information on likely environmental losses for the area under consideration an N management practice can be devised for particular crops which meets the requirements of sustainability (i.e., yield as well as safe use of N). Furthermore, yield expectation can be used to modify N recommendations. For instance, if the management system under consideration will support only 70 % of the yield achieved on research farms, the amount of N recommended can be reduced accordingly.

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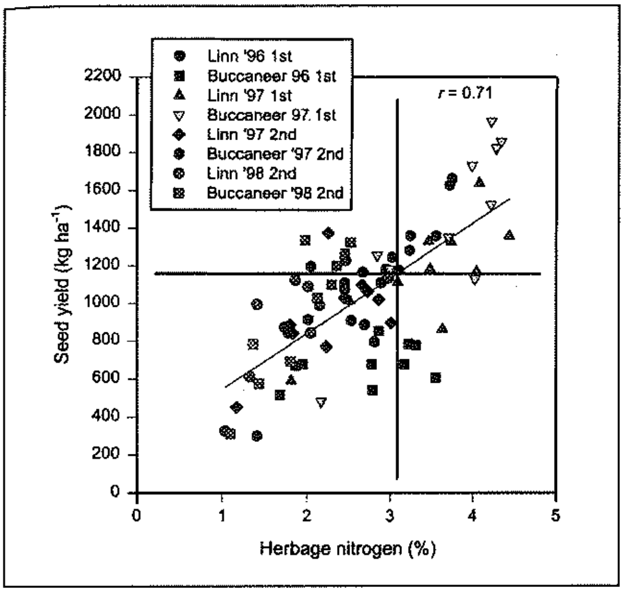

Fig. 2. **Relationship between herbage N concentration (%) fourteen days after application of early spring nitrogen and perennial ryegrass seed yield. Cate Nelson separation technique (Cate and Nelson, 1965) is used to show a critical threshold. (Data for cv. Grasslands Nui are presented in Rowarth *et al.*, 1998.)**

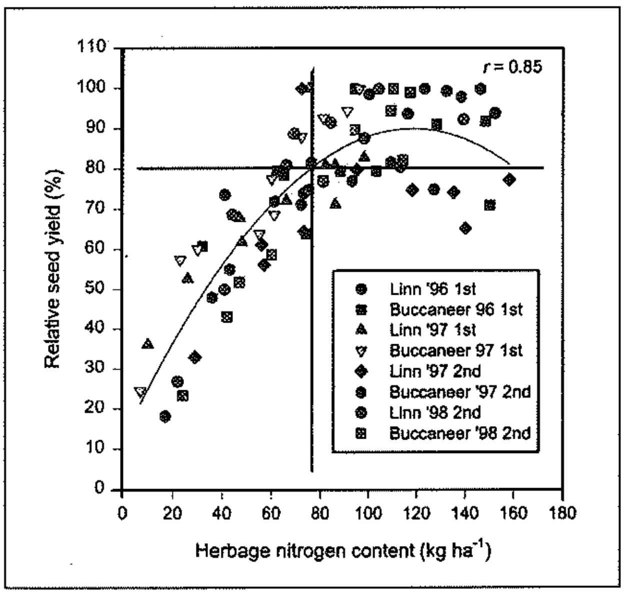

Fig. 3. **Relationship between herbage N content (kg ha^{-1}) fourteen days after application of early spring nitrogen and perennial ryegrass seed yield relative to the maximum yield for each trial. Cate Nelson separation technique (Cate and Nelson, 1965) is used to show a critical threshold. (Data for cv. Grasslands Nui are presented in Rowarth *et al.*, 1998.)**

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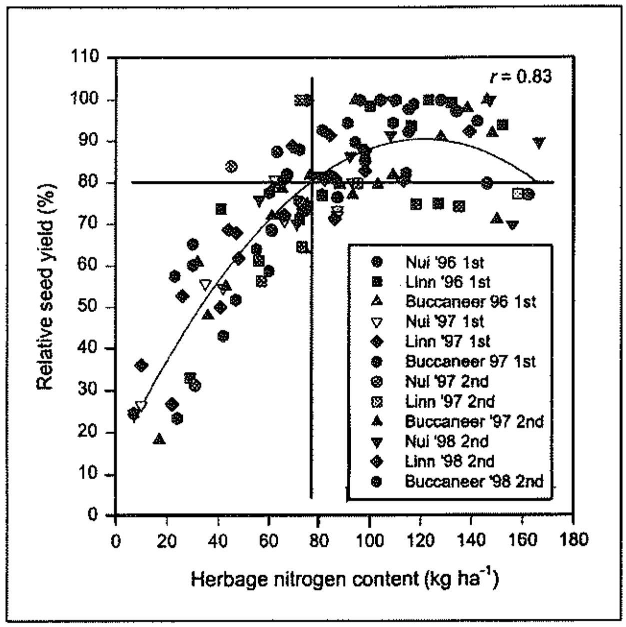

Fig. 4. **Relationship between herbage N content (kg ha^{-1}) fourteen days after application of early spring nitrogen and perennial ryegrass seed yield relative to the maximum yield for each trial. Cate Nelson separation technique (Cate and Nelson, 1965) is used to show a critical threshold.**

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