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Sustainability Issues Involved with Nitrogen Fertilizer Use in Perennial Ryegrass (*Lolium perenne* L.) Seed Crops

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ABSTRACT

A sustainable management practice has been defined as an activity which maintains and enhances productivity, is economically viable, decreases risks to production, decreases risks to the environment, and is socially acceptable. Results from a three year research programme which examined the efficient use of nitrogen (N) fertilizer applied to a perennial ryegrass (*Lolium perenne* L.) seed crop, were related to these five objectives of sustainability. N fertilizer application was required for economic viability as ryegrass seed production from unfertilized plots did not cover costs of production. N fertilizer applied during autumn, late winter and spring maximised seed yields and N fertilizer use efficiency, but late winter and spring application had a greater effect on yields and fertilizer use efficiency than fertilizer N applied during autumn. N fertilizer applied in autumn also had a considerably higher risk of losses from leaching and denitrification than N fertilizer applied in late winter and spring. Increases in seed N concentration and thousand seed weight were associated with increased fertilizer application and helped to explain differences in seed emergence at autumn and winter soil temperatures. Increases in N use efficiency through improved fertilizer timing may help achieve the goals of sustainability.

Additional index words: sustainability, nitrogen fertilizer, ryegrass seed production.

INTRODUCTION

Nitrogen (N) fertilizer increases plant growth (Thomson, Roberts, Judd and Clough, 1991), decreases establishment time (Rowarth, Pennell, Fraser and Baird, 1996) and increases perennial ryegrass (*Lolium perenne* L.) seed yields (Rowarth, 1997a; b). Research in New Zealand had previously indicated seed yield responses to N fertilizer at rates above 115 kg N ha^{-1} were unlikely (Brown, 1980; Hampton, 1987). However these seed yields were approximately 1100 kg N ha^{-1} (Brown, 1980; Hampton, 1987). More recently, perennial ryegrass seed yields greater than 2000 kg ha^{-1} have been produced after applying N fertilizer totalling 250 kg N ha^{-1} (Rolston and McCloy, 1997). No research has been reported which traces N fertilizer applied to a ryegrass seed crop, but in browntop (*Agrostis capillaris* L.) as N fertilizer application rate increased, N recovery in the crop decreased (Jin, Rowarth, Scott and Sedcole, 1996).

Concern about green-house gas emissions and ground water quality has resulted in restrictions on fertilizer use in some regions of New Zealand (Williams, Rowarth and Tregurtha, 1997) and sparked debate over the sustainability of N fertilizer applications. Concepts of sustainability differ widely and definitions tend to reflect national concerns (Syers, Hamblin and Pushparajah, 1994; Cornforth, 1999). During an internationally-coordinated effort to create a framework for the establishment of sustainable land management a definition, based on five objectives, was formulated (Smyth and Dumanski, 1994):

"Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as simultaneously to:

- maintain and enhance productivity
- decrease risks to production
- protect the potential of natural resources and prevent the degradation of soil and water quality
- be economically viable
- be socially acceptable."

Land management practices should therefore be tested by monitoring appropriate indicators to achieve the five objectives of sustainability. The aim of this investigation was to examine the sustainability of N fertilizer use in perennial ryegrass seed crops. Monolith lysimeters and ^{15}N-labelled fertilizer were used to trace fertilizer N movement within the atmosphere, crop, soil and leachates. Several different rates and applications times (autumn, late winter and/or spring) were used.

MATERIALS AND METHODS

Lysimeter collection and treatments

Twenty four monolith lysimeters (500 mm diameter, 700 mm deep) of a deep-profiled Templeton silt loam on a sandy loam (Udic Ustochrept, USDA), were extracted from a 7 year old pasture in March 1996 on Lincoln University farm land,

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Canterbury, New Zealand, following methods described by Cameron, Smith, McLay, Fraser, McPherson, Harrison and Harbottle (1992). Lysimeters were transported to Lincoln University, and installed in a trench, with the soil surface of the lysimeter at ground level. These lysimeters were destructively sampled after seed harvest (December 1996) and replaced in March 1997 with lysimeters extracted from the same field site as in 1996. On the 20th March 1996 and 22nd March 1997, the lysimeters were sprayed with glyphosate at the recommended rate, and on the 8th April 1996 and 1997 remaining pasture was cut to the soil surface and removed. Lysimeters were hand cultivated to a nominal 150 mm depth on the 10th April 1996 and 12th April 1997, and 150 kg superphosphate ha^{-1} was applied to match farmer practice. Lysimeters were sown with perennial ryegrass (*Lolium perenne* L.) cv. Grasslands Nui in three rows, 150 mm apart, across the monolith on the 26th April 1996 and 28th April 1997 at the equivalent of 10 kg seed ha^{-1}.

To allow N fertilizer treatments in 1997 to continue through a second winter, small lysimeters (diameter, 180 mm; length, 300 mm) were extracted from the large lysimeters (diameter, 500 mm; length, 700 mm) used in 1997 during destructive sampling, following methods described in Cameron *et al.* (1992). Small lysimeters were installed in a trench with the soil surface of the lysimeter at ground level in January 1998.

The rates and timing for applying granular urea N and 10.5 % ^{15}N enriched granular urea in 1996 and 1997 are summarised in Table 1. The three application times for both years were: (1) 4 weeks after sowing when soil temperature at 9 am at 100 mm depth was above 8°C (15th May 1996 and 18th May 1997) (autumn), (2) when soil temperatures at 9 am at 100 mm depth rose above 4.5°C and N uptake resumed (Hoglund, 1980) (10th August 1997 and 5th August 1997) (winter), and (3) when soil temperature at 9 am at 100 mm depth was approximately 8°C in spring and N response is reported to be at its highest (Hampton, 1987) (20th September 1996 and 16th September 1997) (spring) (note: application rates above 50 kg N ha^{-1} were split 50:50, 10 days apart). Application rates in 1996 totalled 0 (control), 150, 200 or 250 kg N ha^{-1}. These were increased in 1997 to totals of 0, 200, 250, 300 or 350 kg N ha^{-1}. Treatments were replicated four times in a randomised block design.

Tebuconazole (750 mL ha^{-1}) was applied to prevent fungal diseases on the 20th October and 10th November in 1996 and on the 20th August, 23rd October and 13th November in 1997; weeds were controlled by hand.

To monitor soil moisture status, permanent tensiometers were inserted horizontally at 150 mm depth into one lysimeter from each N treatment. The tensiometers were read at 10.30 am and 3.30 pm daily. The soil moisture content was calculated from the moisture release characteristics of the soil (Klute, 1986). To prevent moisture stress (Rowarth, Chapman, Novis and Rolston, 1997), soils were maintained between 70 and 90 % of field capacity by the application of 13 mm of irrigation water when tensiometers indicated a trigger level of 70 % field capacity had been reached. Irrigation was applied to individual treatments no later than 8.30 am. No drainage was found from beneath any lysimeters during the irrigation period. Irrigation ceased when the flag leaves from each treatment dried; this occurred between 16 and 20 days before harvest in 1996 and 1997.

Data collection and analysis

Ryegrass seed and herbage was harvested from the large lysimeters by hand between the 22nd and 26th December of 1996 and 1997, as the seed heads ripened. Pasture was harvested from the small lysimeters by hand on the 10th September 1998 after winter leaching had stopped. Harvested material (shoot (seed and herbage) and root) from the 3 sets of lysimeters was placed in paper bags and air-dried (average ≈20°C). Harvested material (seed and herbage) was threshed using a Kirkpeltz thresher. Seed was dressed to a thousand seed weight of over 1.85g using a Kamus Westrup seed dresser. Seed yields and herbage yields were then weighed. Floret site utilisation (FSU) was calculated as:

$$\text{FSU} = \frac{\text{Actual seed number}}{\text{Potential seed number}}$$

where:

Actual seed number = seed yield ($g\ m^{-2}$) / TSW X 1000

Potential seed number = florets $head^{-1}$ x heads m^{-2}

N use efficiency (NUE) (Novoa and Loomis, 1981) was calculated as:

$$\text{NUE} = \frac{\text{Seed yield with fertilizer } (g\ m^{-2}) \ - \text{seed yield from control } (g\ m^{-2})}{\text{N fertilizer applied } (g\ m^{-2})}$$

Representative sub-samples of all harvested material (seed, herbage and roots) were finely ground (< 250 Tm) using a 'Cyclotec 1092' sample mill (Tecator, Sweden) and weighed into aluminium foil capsules. The capsules were then inserted directly into a Tracermass stable isotope analyser, used in conjunction with the Roboprep-CN biological sample converter (Europa Scientific, UK) to analyse for total N and $^{15}N/^{14}N$ ratio. The percent recovery of the applied urea-^{15}N was calculated using the following formula (Cabrera and Kissel, 1989):

$$\text{N recovered } \% = \frac{p(c-b)\ \text{x}\ 100}{f(a-b)} \qquad (1)$$

where:

p = moles of N in sample,

f = moles of N in urea applied,

c = atom % ^{15}N abundance in sample,

a = atom % ^{15}N abundance in the urea,

b = atom % ^{15}N abundance in sample without urea input.

At the end of each experiment (between 5th and 15th January 1996 and 1997, and 10th September 1998) each lysimeter was removed from the trench and carefully sliced into 50 mm depth increments for analysis. Bulk density, moisture content, mineral N, total N and $^{15}N/^{14}N$ ratio of the soil was determined for each depth. Representative subsamples from each depth were ground very finely (< 150 Tm) using a Tema mill grinder (N.V. Tema, The Netherlands) and analysed for total soil-N and soil ^{15}N analyses, as described earlier. Percentage recovery of applied urea-^{15}N was calculated using equation 1.

Table 1. Lysimeter experiment design with the application rates and timings of ^{15}N-labelled and unlabelled nitrogen (N) fertilizer in the 1996 and 1997 seasons.

Year	Treatment	^{15}N-labelled fertilizer applied		Unlabelled N fertilizer applied		Total N
		Timing	Rate (kg N ha^{-1})	Timing	Rate (kg N ha^{-1})	(kg N ha^{-1})
1996	0 + 0 + 0[1]		0		0	0
	50[2] +50 + 50	autumn	50	winter, spring	50, 50	150
	50[2] + 0 +150	autumn	50	spring	150	200
	0 +50[2] +150	winter	50	spring	150	200
	0 + 0 +150[2]	spring	150		0	150
	50 +50 +150[2]	spring	150	autumn, winter	50, 50	250
1997	0 + 0 + 0		0		0	0
	50[2] + 50 +200	autumn	50	winter, spring	50, 200	300
	0 + 50[2] +150	winter	50	spring	150	200
	50 +100[2] +150	winter	100	autumn, spring	50, 150	300
	50 + 50 +150[2]	spring	150	autumn, winter	50, 50	250
	50 +100 +200[2]	spring	200	autumn, winter	50, 100	350

1 N rates (kg N ha^{-1}) in autumn + winter + spring
2 Indicates ^{15}N application
note: higher rates of N were applied in 1997 in an attempt to reach a plateau in N uptake.

Leachates were returned to the laboratory (for storage below 0°C, prior to analysis) within 2 days of any drainage event (to minimise N losses) or when the majority of lysimeters had approximately 2 litres of drainage from the large lysimeters or 150 mL from the small lysimeters, whichever came first. Total volumes were measured and sub-samples (100 mL) taken for chemical analysis. Nitrate and ammonium concentrations were determined by ion exchange chromatography (Waters, USA) and automated flow injection analysis (Tecator, Sweden). The leachates were prepared for ^{15}N analyses using a modified diffusion method described by Brooks, Stark, McInteer and Preston (1989). Samples were then analysed for ^{15}N/^{14}N ratio as described earlier. Percent recovery of the applied urea-^{15}N was calculated using equation 1.

Volatilization losses were measured for 25 days after each N fertilizer application using an enclosure method (Sherlock and Goh, 1985). All N fertilizer application rates were replicated three times. Ambient air was drawn continuously through each enclosure at approximately 20 litres per minute. The flow from each enclosure was passed through a trap containing 50 mL of 0.05 M H_2SO_4 which was changed every 24 hours. Ammonium concentration was determined by automated flow injection analysis (Tecator, Sweden).

It was assumed that any ^{15}N-labelled fertilizer which was not accounted for in the measured components represented the amount lost by denitrification losses (Fraser, Cameron and Sherlock, 1994).

Gross margins were calculated from an average seed price for cv. Grasslands Nui seed in 1997 (NZ $1.20 kg^{-1} seed) and compared with production costs from an intensive cropping farm in Canterbury on a medium soil type (Burtt, 1998). All costs were rounded to the nearest dollar. The value of N lost via leaching, volatilization and denitrification was estimated by calculating the cost of fertilizer N required to replace losses. Several assumptions (Burtt, 1998) were made:

- cultivation work was performed by the farmer
- fertilizer spreading, pest control, harvesting and cartage were performed by a contractor
- phosphate and urea applications were applied separately
- N losses were replaced by applying N fertilizer
- the farmer had spray irrigation
- the property was within 100 km of fertilizer supplier and seed purchaser
- hand harvested plots yield 20 % more than machine harvested plots (Hampton, J.G., Lincoln University, pers. comm., 1999).

The ratios between total N lost and N recovered in either seed or seed and herbage were calculated to provide indices of environmental risks relative to N retained within the crop:

total N losses : seed N recovery
and total N losses : herbage N recovery.

The seedling emergence of seed harvested from the lysimeters during the 1996 and 1997 seasons was measured from soil at 5 °C or 10 °C. Seed material was analyzed for N concentration (Bremner, 1996) and thousand seed weight (TSW) (ISTA, 1996).

Results were analysed using the Minitab 9.2 (© 1993, Minitab Inc.) computer programme. Analysis of variance was performed with least significant differences at P=0.05, calculated from the error mean sum of the squares.

RESULTS

Seed yields (309 g m^{-2} in 1996 and 451 g m^{-2} in 1997), reproductive head numbers (2324 heads m^{-2} in 1996 and 2638 heads m^{-2} in 1997) and seeds per head (60 seeds per head in 1996 and 75 seeds per head in 1997) were greatest when N fertilizer was applied in autumn (50 kg N ha^{-1}), winter (50 or 100 kg N ha^{-1}) and spring (150 kg N ha^{-1}) but were not increased by the use of 200 kg N ha^{-1} in spring. NUE was also highest in these treatments but did not necessarily differ significantly from that of other treatments (Table 2). Linear regressions fitted to the responses between seed yield and N fertilizer application rate (R^2=0.86), reproductive head number (R^2=0.77) and seeds per head (R^2=0.92) gave significant relationships for combined data from 1996 and 1997. Florets per head were increased significantly ($P<0.05$) with increases

Table 2. Effect of nitrogen (N) fertilizer application rate and timing on ryegrass seed yield, head numbers, seeds per head, florets per head, floret site utilization (FSU), N fertilizer use efficiency (NUE) and gross margins for cv. Grasslands Nui in the 1996 and 1997 seasons.

Year	Treatment	Seed yield (g m^{-2})	Heads numbers (m^{-2})	Seeds per head	Florets per head	FSU	NUE[1]	Gross Margin[2] (\$ ha^{-1})
1996	0+ 0+ 0[3]	69	1200	30	103	29	-	-476
	50+ 50+ 50	214	2065	52	129	40	9.7	573
	0+ 0+150	194	1968	50	131	38	8.3	388
	50+ 0+150	206	2124	46	153	30	6.8	441
	0+ 50+150	256	2108	56	161	35	9.4	840
	50+ 50+150	309	2324	60	162	37	9.6	1175
	LSD P<0.05	38	128	3	23	5	1.5	115
1997	0+ 0+ 0	116	1735	30	152	20	-	-237
	0+ 50+150	316	2135	65	176	37	10.0	1818
	50+ 50+150	388	2394	70	189	37	10.9	1149
	50+100+150	451	2638	75	193	39	11.2	2080
	50+ 50+200	418	2470	65	187	35	10.0	1647
	50+100+200	441	2605	71	192	37	9.3	1953
	LSD P<0.05	47	224	4	11	4	n.s.	189

[1] *NUE* = $\frac{\textit{Seed yield per treatment- seed yield from control}}{\textit{N fertilizer applied}}$

[2] *Based on a seed price of NZ S1.20 kg*$^{-1}$.

[3] *N rates (kg N ha*$^{-1}$*) in autumn + winter + spring*

Table 3. Full ^{15}N balance showing the effect of nitrogen (N) fertilizer application rate and timing on percentage of N fertilizer lost via leaching and volatilization and recovered in the crop, soil and roots in the 1996 and 1997 seasons.

Year	Treatment	Volatil[1] (%)	Leaching (%)	Crop (%)	Soil and roots (%)	Total (%)	Unacc[2] (%)
1996	50[3]+ 50+ 50[4]	4.6	8.3	16.0	68.8	97.7	2.3
	0+ 0+150[3]	9.7	0.0	33.3	52.0	95.0	5.0
	50[3]+ 0+150	4.6	6.1	18.8	70.0	99.5	0.5
	0+ 50[3]+150	3.8	0.0	32.5	62.5	98.7	1.3
	50+ 50+150[3]	9.7	0.0	49.5	38.2	97.4	2.6
1997	0+ 50[3]+150	8.6	0.0	34.9	52.2	95.7	4.3
	50+ 50+150[3]	13.8	0.0	44.7	29.8	88.3	11.7
	50+100[3]+150	9.6	0.0	47.6	42.7	99.9	0.1
	50[3]+ 50+200	9.8	7.8	19.1	39.0	75.7	24.3
	50+100+200[3]	16.9	0.0	45.0	29.8	91.7	8.3

[1] *Volatilization*

[2] *N not accounted for in the balance (denitrification)*

[3] *Indicates* ^{15}N *application*

[4] *N rates (kg N ha*$^{-1}$*) in autumn + winter + spring*

in N fertilizer in 1996 and 1997 (Table 2). Floret site utilization increased significantly ($P<0.05$) with increases in N fertilizer irrespective of the rate in 1997; a similar tendency was apparent in 1996 except where autumn N was not followed by winter N application (Table 2).

Gross margin analysis indicated that ryegrass seed production was economically unsustainable without N fertilizer application as income from seed yields and hay did not cover production costs (Table 2). Increases in gross margins were linearly related to N fertilizer application rate ($R^2 = 0.92$ both years combined) and the effect of N fertilizer on seed yields ($R^2 = 0.999$), as seed is the major form of income in herbage seed production.

On average 60% of the ^{15}N-labelled fertilizer losses resulted from ammonia volatilization which increased with increasing N fertilizer application rate ($R^2 = 0.90$ both years combined) (Table 3). Losses tended to be higher in spring than in autumn and winter (Table 3) as spring conditions were warmer.

Application date had no effect on denitrification losses during 1996 and average losses were small (2 %) (Table 3). However, wetter conditions in May 1997 immediately after autumn N fertilizer application, as compared with 1996 (data not shown), resulted in much larger autumn N fertilizer denitrification losses (24 %) as compared with spring (10 %) or winter (2 %) losses (Table 3).

Table 4. The effect of nitrogen (N) fertilizer application timing and rate on risk: benefit analysis.

Application timing and rate (kg N ha^{-1})	N loss:seed N[1]	N loss:herbage N[2]
Autumn 50	3.3	2.1
Winter 50	0.7	0.4
Winter 100	0.3	0.8
Spring 150	1.0	0.7
Spring 200	1.7	1.0

[1] Total N losses (kg N ha^{-1}) / total seed N recovery (kg N ha^{-1})

[2] Total N losses (kg N ha^{-1}) / total herbage recovery (kg N ha^{-1})

Table 5. The effect of nitrogen (N) fertilizer application timing and rate on seed N concentration (N conc.) and thousand seed weight (TSW) and emergence following sowing at 5°C and 10°C soil temperatures in the 1996 and 1997 seasons.

		Seed component		Emergence from soil (%)[2]	
Year	Treatment	TSW (g)	N conc[1] (%)	5 °C	10 °C
1996	0+ 0+ 0[3]	1.90	1.51	65	60
	50+ 50+ 50	1.99	1.57	69	72
	0+ 0+150	1.96	1.68	74	77
	50+ 0+150	2.09	1.61	71	75
	0+ 50+150	2.15	1.68	75	80
	50+ 50+150	2.20	1.71	76	80
	LSD P<0.05	0.10	0.12	n.s.	8
1997	0+ 0+ 0	2.26	1.24	69	74
	0+ 50+150	2.30	1.35	73	78
	50+ 50+150	2.35	1.49	83	87
	50+100+150	2.44	1.48	91	95
	50+ 50+200	2.42	1.45	81	85
	50+100+200	2.43	1.52	80	85
	LSD P<0.05	0.10	0.04	4	4

[1] concentration

[2] LSD ($P<0.05$) between soil temperatures is 2.6 and 2.4 in 1996 and 1997, respectively.

[3] N rates (kg N ha^{-1}) in autumn + winter + spring

Total rainfall during the study period (383 mm in 1996 and 322 mm in 1997) was similar to the long-term April-September average (335 mm). Total drainage (mean) below the twenty four lysimeters was 185 mm in 1996 and 150 mm in 1997. ^{15}N-labelled fertilizer applied during winter or spring was not found in leachates during 1996 or 1997 (Table 3). The addition of autumn N fertilizer contributed only a small amount to nitrate leaching losses (3.9 and 4.3 kg N ha^{-1}) during 1996 and 1997 (Table 3); this did not contribute to a significant increase in total leaching losses (data not presented). Soil-derived N contributed 78 and 88 % of the nitrate leached beneath autumn fertilized lysimeters in 1996 and 1997, respectively, but more soil-derived N was leached below autumn fertilized lysimeters (19 and 33 kg N ha^{-1}) than unfertilized lysimeters (14 and 23 kg N ha^{-1}).

On average, recovery of winter (40 %) and spring (43 %) applied ^{15}N-labelled fertilizer in the crop at seed harvest was much higher than autumn (18 %) applied ^{15}N-labelled fertilizer. Recovery in the roots and soil of ^{15}N-labelled fertilizer applied in winter (52 %) and autumn (59 %) was greater than N fertilizer applied in spring (37 %) (Table 3).

Risk : benefit analysis indicated that autumn N fertilizer, and spring N fertilizer at 200 kg N ha^{-1}, were associated with the greatest risks of loss and the smallest benefits in terms of seed and herbage N recovery (Table 4). N fertilizer applied during winter, and spring applications up to 150 kg N ha^{-1}, had substantial benefits with lower risk (Table 4).

TSW was lighter and N concentration was greater in 1996 than in 1997 (Table 5). Seed N concentration and TSW were significantly ($P<0.05$) affected by N fertilizer application and tended to increase with increasing N fertilizer application rate in 1996 and 1997 (Table 5). Seedling emergence was positively correlated with seed N concentration (5 °C, r=0.80 and 0.82; 10 °C, r=0.70 and 0.81 in 1996 and 1997 seed, respectively) and TSW (5 °C, r=0.71 and 0.76; 10 °C, r=0.58 and 0.75 in 1996 and 1997 seed, respectively) (Table 5). Mean seedling emergence was slightly but significantly ($P<0.05$) increased (from 71 % to 75 % in 1996 and from 80 % to 85 % in 1997) when soil temperature was increased from 5 to 10 °C.

Leaching losses (<0.07 kg N ha^{-1}) and pasture uptake (0.6 to 4 kg N ha^{-1}) of residual ^{15}N-labelled fertilizer from the small lysimeters during the 9 month period after seed harvest were

Table 6. The effect of ^{15}N-labelled fertilizer application rate and timing in 1997 on the distribution of ^{15}N at harvest 1998.

Treatment	Leaching (kg N ha^{-1})	Herbage (kg N ha^{-1})	Roots + Soil (kg N ha^{-1})	Total Recovery 1998 (kg N ha^{-1})	Total Recovery 1997 (kg N ha^{-1})
0+ 50^{1}+150^{2}	0.05	1.0	22.2	23.3	23.6
50+ 50+150^{1}	0.04	2.9	41.5	44.4	41.4
50+100^{1}+150	0.07	2.0	36.4	38.5	40.0
50^{1}+ 50+200	0.06	0.6	16.1	16.7	17.8
50+100+200^{1}	0.05	4.0	55.1	59.2	55.2

[1] *Indicates ^{15}N application*

[2] *N rates (kg N ha^{-1}) in autumn + winter + spring*

Table 7. The effect of fertilizer application treatment in 1997 on root mass (kg ha^{-1}) at seed harvest in 1997 and pasture harvest in 1998.

Treatment	Root mass (kg ha^{-1}) 1997	Root mass (kg ha^{-1}) 1998
0+ 0+ 0^{1}	4640	19023
0+ 50^{2}+150	8697	27158
50+ 50+150^{2}	9658	27443
50+100^{2}+150	10471	30317
50^{2}+ 50+200	10990	31780
50+100+200^{2}	10728	30322
LSD P<0.05	2636	4736

small as residual ^{15}N-labelled fertilizer within the soil and ryegrass roots at seed harvest in 1997 (18 to 55 kg N ha^{-1}) was mostly still in these components at pasture harvest in 1998 (16 to 59 kg N ha^{-1}) (Table 6). Root mass was significantly (P<0.05) greater in fertilized treatments than unfertilized treatments at seed harvest in 1997 and pasture harvest in 1998 (Table 7). Total N leaching losses and average nitrate concentration of leachates during winter drainage were not affected by N fertilizer application in 1997, and ranged from 0.9 to 1.1 kg N ha^{-1} and 0.2 to 0.3 Tg mL^{-1}, respectively.

DISCUSSION

Maintain and enhance productivity

N and water availability are the most common limitations to crop production (Rowarth, 1997a; b). In this study under zero moisture stress, high N fertilizer application rates of 250 to 300 kg N ha^{-1} produced ryegrass seed yields some 30-50 % greater than those produced from N rates (100 to 130 kg N ha^{-1}) previously considered optimal (Brown, 1980; Hampton, 1987). This is likely to have resulted from the combined effect of improved N fertilizer timing and particularly the absence of moisture stress. Although, the effect of N fertilizer on head numbers is often the major determinant of seed yield (Rolston, Rowarth, DeFilippi and Archie, 1994; Rowarth, Boelt, Hampton, Marshall, Rolston, Sicard, Silberstein, Sedcole and Young, 1998) more seed yield variability in the current research was accounted for by seeds per head (R^2=0.92) than head number (R^2=0.77). However, a combination of increased head numbers (increased 52 % to 2638 heads m^{-2}), florets per head (increased 27 % to 193 florets per head), TSW (increased 7 % to 2.43 g), FSU (increased 95% to 39%) and seeds per head (increased 137 % to 75 seeds per head) relative to unfertilized plots, resulted in the high maximum seed yield (equivalent to 4514 kg ha^{-1}) recorded. This suggests that under zero moisture stress and improved fertilizer timing, high yield potential (heads and florets per head) and yield fulfillment (seeds per head and FSU) of good quality seed (TSW) can be achieved. Field scale testing to confirm these results is required, as these were small plots where every effort was made to ensure that N was the only factor affecting crop growth.

Sustainable crop production also requires maximum NUE (Campbell, Myers and Curtin, 1995) which is achieved when N supply matches crop N demand (Rowarth, 1997a). Although measurement of crop demand by destructive sampling was not possible during the current research, an N fertilizer management plan where fertilizer N was applied in autumn, winter and spring appeared to improve crop nutrition in contrast to spring, autumn/spring or winter/spring applications, as seed yield was increased and NUE was high. This suggests that N fertilizer application in autumn, winter and spring was required to meet the seasonal pattern of ryegrass N demand under the conditions of this experiment (no moisture stress). The balance between autumn, winter and spring applications is important, as excessive N fertilizer (spring applications of 200 kg N ha^{-1}) or inadequate N fertilizer (no autumn and/or winter N fertilizer), under conditions of no moisture stress, will not increase seed yield or NUE (Table 2). Furthermore, a compromise between the production benefits and environmental impacts (discussed in a later section) of autumn applied N fertilizer may also be required.

Being economically viable
A prime consideration in achieving sustainability is having an economically viable farming operation. At current seed prices (Burtt, 1998) for cv. Grasslands Nui, perennial ryegrass seed production is not sustainable without N fertilizer application (Table 2).

The contribution of fertilizer use to net returns is dependent on the likelihood of gaining sufficient increase in crop yield to overcome the added cost of inputs, and is affected by seed price, weather conditions and NUE. In the experiments reported, and at the current price for cv. Grasslands Nui seed, any increase in seed yield resulting from N fertilizer applied to a fully irrigated system increased profit. At N fertilizer application rates above 150 kg N ha^{-1} gross margins tended to increase with increasing NUE. This emphasizes the importance of matching crop demand and N fertilizer supply.

Ryegrass seed production in a mixed cropping system has further benefits such as increasing soil organic matter and improving soil structure (Haynes, Swift and Stephan, 1991; Haynes and Francis, 1993); these aspects are discussed in a later section. Ryegrass seed production also allows the use of herbicides to control weeds which are uncontrollable in other crops, and the crop is often used as a source of stock feed during vegetative growth (Hampton and Rowarth, 1998). Pasture is a vital restorative phase in a mixed cropping system and its continued use is an essential component of the sustainability of this system (Haynes and Francis, 1990).

Decrease risks to production
Perennial ryegrass seed yields vary from year to year, even when water does not limit growth, due to such factors as diseases, weeds and insects, plus climatic conditions at harvest (Hampton and Rowarth, 1998). Under the near-ideal conditions of the lysimeters applying N fertilizer substantially decreased the variability of seed yields between 1996 and 1997 from 40 % when no N fertilizer was applied to 20-25 % when N fertilizer was applied (Table 2). However, in perennial ryegrass production areas in New Zealand, water, rather than N, is often the most limiting crop growth factor (Rolston *et al.*, 1994). Seed yield does not respond to fertilizer N when moisture limits growth (Hebblethwaite, 1977; Rolston *et al.*, 1994); it is likely that the relationship between N and soil moisture will influence year-to-year yield fluctuations.

The risk of N leaching losses is greatest during winter when rainfall is high and evapotranspiration is low (Cameron and Haynes, 1986). In autumn sown crops, N leaching losses may be decreased by changing cultivation from mid to late autumn, as colder soil temperatures reduce the mineralization of soil N before winter leaching (Francis, Haynes, Sparling, Ross and Williams, 1992). However, decreasing soil temperature decreased seedling emergence, a result also reported for other herbage species (Charlton, Hampton and Scott, 1986; Bennett, Rowarth and Jin, 1998). Seedling emergence was however higher in N fertilizer treatments where seed N concentration and TSW were greatest, at both soil temperatures (Table 5). This agrees with recent research which has suggested that seed characteristics such as seed N concentration and content may be related to seed vigour (Jin *et al.*, 1996; Bennett *et al.*, 1998). These seed quality components were maximized when autumn, winter and spring fertilizer was applied (Table 5). This suggests that applying fertilizer to match crop demand improves seed quality and that sowing seeds with higher N concentration and TSW could reduce the risks of poor establishment at colder temperatures while achieving environmental goals.

Protect the potential of natural resources and prevent the degradation of soil and water quality
The period of time given to either cropping (i.e. cereals) or ryegrass within a Canterbury mixed cropping system varies with the relative profitability of the two forms of farming and the need to maintain good soil structure (Haynes *et al.*, 1991). It has been postulated that improvement in soil structure under ryegrass is associated with a high root mass resulting in greater rhizodeposition of carbohydrate binding agents which increase aggregate stability (Haynes and Beare, 1997). Thus crops with the greatest root mass often result in the greatest improvement in aggregation (Stone and Buttery, 1989; Kay, 1990; Perfect, Kay, Van Loon, Sheard and Pojasok, 1990; Haynes and Francis, 1993; Haynes and Beare, 1997). N fertilizer treatments had almost double the root mass in comparison with unfertilized treatments and so fertilizer may help improve soil structure (Table 7). Hence, N fertilizer use with ryegrass crops can help to improve soil quality (Rowarth, Cookson, Williams and Cameron, 1999)

Unlike N leaching losses, no international limits to gaseous N losses have been established, even though the ecological effects of gaseous N emissions may affect society on a much wider scale than nitrate leaching (Powlson, 1997). The major pathways of fertilizer N losses in this research were via gaseous N emissions (Table 3). Since the reduction of green house gas emissions is a world wide objective (B;ckman, 1994) gaseous N emissions may have a large effect on the future sustainability of this production system.

At present the major environmental issue of N fertilizer use is water quality in view of stringent limits on the permitted concentrations of nitrate in water ways (Powlson, 1997). Under Canterbury weather conditions, leaching losses largely occur during winter months (Cameron and Haynes, 1986; McLenaghen, Lampkin, Daly and Deo, 1996) and nitrate present in the soil during this period is at risk of leaching. Results from the current research indicate that nitrate present in the soil during winter in a ryegrass seed crop largely resulted from the mineralization of soil N at cultivation. Although the direct effect of autumn fertilizer on leaching losses from an autumn cultivated soil is debatable, N fertilizer applied in the autumn increases the risk of winter N leaching losses (Powlson, Hart, Pruden and Jenkinson, 1986) and protocols to reduce this risk must be established.

The short term use of N fertilizer generally affects N losses only during a growing season (Bhogal, Young, Sylvester-Bradley, O'Donnell and Ralph, 1997). Similarly, results from the current research indicated that applying large amounts of N fertilizer (up to 350 kg N ha^{-1}) did not significantly affect N losses during the nine month period following seed harvest. Applying fertilizer N in autumn and winter decreased the amount of spring applied N fertilizer remaining in the soil during the nine months after seed harvest. The reduction was from 52 % (when no N was applied in autumn and winter) to 38 % (when N was applied in autumn and winter). This decrease in soil N was related to increased crop uptake of spring fertilizer N when autumn and winter fertilizer were applied as compared with a single spring application (Table 3). This suggests that improved prediction of crop N demand and hence increased NUE can decrease applied N recovered in the soil and minimize the risks of N losses in the future.

Be socially acceptable
It is likely that N fertilizer application will need to continue at reasonably high rates in order to ensure the economic viability of ryegrass seed production. Present environmental concerns regarding intensive farming practices, such as N fertilizer application, will nevertheless have to be addressed.

More accurate matching of fertilizer N applications with crop requirements may be one step in helping change the public perception of fertilizer use as environmentally damaging (Bailey, 1993). Certainly the current research indicates that, under non limiting moisture conditions, the balance between N fertilizer timing and rate was able to increase NUE.

Risk : benefit analysis is another tool which may improve public perceptions of fertilizer application. A risk : benefit analysis in the current research emphasized the importance of matching N fertilizer supply with crop demand. There was a tendency for losses to be greater when N fertilizer was applied at rates where crop and seed recovery were low, hence increasing the risk of environmental pollution.

Public awareness of other mixed cropping farming practices which are environmentally sound need to be increased; examples are the use of restorative and depletive crops, and other rotational practices such as long periods in pasture. The challenge to the farming and agricultural research community is, therefore, to improve the efficiency of agricultural practices such as fertilizer use, to minimize environmental damage and to keep the public aware of these improvements, thereby helping to limit negative perceptions of agriculture.

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REFERENCES

1. Bailey, J.S. 1993. Sustainable fertiliser use. *Proceedings of The Fertiliser Society* 343: 1-44.

2. Bennett, J.S., Rowarth, J.S. and Jin, Q.F. 1998. Seed nitrogen and potassium nitrate influence browntop (*Agrostis capillaris* L.) and perennial ryegrass (*Lolium perenne* L.) seed performance. *Journal of Applied Seed Production* 16: 77-81.

3. Bhogal, A., Young, S.D., Sylvester-Bradley, R., O'Donnell, F.M. and Ralph, R.L. 1997. Cumulative effects of nitrogen application to winter wheat at Ropsley, UK, from 1978 to 1990. *Journal of Agricultural Science, Cambridge* 129: 1-12.

4. Buckman, O.C. 1994. Best agricultural practice for the protection of air. *Proceedings of The Fertiliser Society* 360: 1-20.

5. Bremner, J.M. 1996. Nitrogen - Total. In: Methods of Soil Analysis, Part 3 - Chemical Methods, (ed. J.M. Bigham), 1085-1121, Soil Science Society of America Inc., Madison, Wisconsin.

6. Brooks, P.D., Stark, J.M., McInteer, B.B. and Preston, T. 1989. Diffusion method to prepare soil extracts for automated nitrogen-15 analysis. *Soil Science Society of America Journal* 53: 1707-1711.

7. Brown, K.R. 1980. Seed production in New Zealand ryegrasses. *New Zealand Journal of Experimental Agriculture* 8:33-39.

8. Burtt, E.S. 1998. Financial budget manual 1998. Lincoln University: Farm Management Group, Applied Management and Computing Division, Canterbury, New Zealand.

9. Cabrera, M.L. and Kissel, D.E. 1989. Review and simplification of calculations in ^{15}N tracer studies. *Fertilizer Research* 20: 11-15.

10. Cameron, K.C. and Haynes, R.J. 1986. Retention and movement of nitrogen in soils. In: Mineral Nitrogen in the Plant - Soil System, (ed. R.J. Haynes), 166-241, Academic Press, Orlando.

11. Cameron, K.C., Smith, N.P., McLay, C.D.A., Fraser, P.M., McPherson, R.J., Harrison, D.F. and Harbottle, P. 1992. Lysimeters without edge flow: an improved design and sampling procedure. *Soil Science Society of America Journal* 56: 1625-1628.

12. Campbell, C.A., Myers, R.J.K. and Curtin, D. 1995. Managing nitrogen for sustainable crop production. *Fertilizer Research* 42: 277-296.

13. Charlton, J.F.L., Hampton, J.G. and Scott, D.J. 1986. Temperature effects on germination of New Zealand herbage grasses. *Proceedings of the New Zealand Grassland Association* 47: 165-172.

14. Cornforth, I.S. 1999. Selecting indicators for assessing sustainable land management. *Journal of Environmental Management*: accepted.

15. Francis, G.S., Haynes, R.J., Sparling, D.J., Ross, D.J. and Williams, P.H. 1992. Nitrogen mineralization, nitrate leaching and crop growth following cultivation of a temporary leguminous pasture in autumn and winter. *Fertilizer Research* 33: 59-70.

16. Fraser, P.M., Cameron, K.C. and Sherlock, R.R. 1994. Lysimeter study of the fate of nitrogen in animal urine returns to irrigation pasture. *European Journal of Soil Science* 45: 439-447.

17. Hampton, J.G. 1987. Effect of nitrogen rate and time of application on seed yield in perennial ryegrass cv. Grasslands Nui. *New Zealand Journal of Experimental Agriculture* 15: 9-16.

18. Hampton, J.G. and Rowarth, J.S. 1998. Ryegrass. In: Practical Herbage Seed Crop Management (ed. J.S. Rowarth), 67-76, Lincoln University Press and Daphne Brasell Associates Ltd, Wellington.

19. Haynes, R.J. and Beare, M.H. 1997. Influence of six crop species on aggregate stability and some labile organic matter fractions. *Soil Biology and Biochemistry* 29: 1647-1653.

20. Haynes, R.J. and Francis, G.S. 1990. Effects of mixed cropping farming systems on changes in soil properties on the Canterbury Plains. *New Zealand Journal of Ecology* 14: 73-82.

21. Haynes, R.J. and Francis, G.S. 1993. Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. *Journal of Soil Science* 44: 665-675.

22. Haynes, R.J., Swift, R.S. and Stephan, R.C. 1991. Influence of mixed cropping factors (pasture - arable) on organic matter content, water stable aggregation and clod porosity in a group of soils. *Soil and Tillage Research* 19: 77-87.

23. Hebblethwaite, P.D. 1977. Irrigation and nitrogen studies in S.23 ryegrass grown for seed 1. Growth, development, seed yield components and seed yield. *Journal of Agricultural Science, Cambridge* 88: 605-614.

24. Hoglund, J. 1980. Nitrogen use on South Island dairy farms. Lincoln College Farmers' Conference, pp. 420-428. Lincoln.

25. ISTA 1996. International rules for seed testing. Supplement to *Seed Science and Technology* 24: 1-335.

26. Jin, Q.F., Rowarth, J.S., Scott, W.R. and Sedcole, J.R. 1996. A study of nitrogen use in a browntop (*Agrostis capillaris* L.) seed crop. *Journal of Applied Seed Production* 14: 31-39.

27. Kay, B.D. 1990. Rates of change of soil structure under different cropping systems. *Advances in Soil Science* 12: 1-52.

28. Klute, A. 1986. Water retention: Laboratory. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, Second Edition, (ed. A. Klute), 635-662, Soil Science Society of America, Madison.

29. McLenaghen, R.D., Lampkin, N.H., Daly, M.L. and Deo, B. 1996. Nitrate leaching from ploughed pasture and the effectiveness of winter catch crops in reducing leaching losses. *New Zealand Journal of Agricultural Research* 39: 413-429.

30. Novoa, R. and Loomis, R.S. 1981. Nitrogen and plant production. *Plant and Soil* 18: 554-563.

31. Perfect, E., Kay, B.D., Van Loon, W.K.P., Sheard, R.W. and Pojasok, T. 1990. Factors influencing soil structural stability within a growing season. *Soil Science Society of America Journal* 54: 173-179.

32. Powlson, D.S. 1997. Integrating agricultural nutrient management with environmental objectives - current state and future prospects. *Proceeding of The Fertiliser Society* 402: 1-44.

33. Powlson, D.S., Hart, P.B.S., Pruden, G. and Jenkinson, D.S. 1986. Recovery of ^{15}N-labelled fertilizer applied in autumn to winter wheat at four sites in eastern England. *Journal of Agricultural Science, Cambridge* 107: 611-620.

34. Rolston, M.P. and McCloy, B.C. 1997. Ryegrass 2000: Technology transfer in ryegrass seed production. *Proceedings of the Agronomy Society of New Zealand* 27: 5-8.

35. Rolston, M.P., Rowarth, J.S., DeFilippi, J.M. and Archie, W.J. 1994. Effects of water and nitrogen on lodging, head numbers and seed yield of high and nil endophyte perennial ryegrass. *Proceedings of the Agronomy Society of New Zealand* 24: 91-94.

36. Rowarth, J.S. 1997a. Nutrients and moisture inputs for grass seed yield. *Journal of Applied Seed Production* 15: 103-110.

37. Rowarth, J.S. 1997b. Nitrogen - impacts on seed yield, seed quality and the environment. *Journal of Applied Seed Production* 15: 23-30.

38. Rowarth J.S., Boelt B., Hampton J.G., Marshall A., Rolston M.P., Sicard G., Silberstein T.B., Sedcole J.R. and Young W.C. III. 1998. The relationship between applied nitrogen, concentration of nitrogen in herbage and seed yield in perennial ryegrass (*Lolium perenne* L.). I. cv. Grasslands Nui at five sites around the globe. *Journal of Applied Seed Production* 16: 105-114.

39. Rowarth, J.S., Pennell, C.G.P., Fraser, T.J. and Baird, D.B. 1996. Pasture response to fertilizer inputs under dairy grazing. *Proceedings of the New Zealand Grassland Association* 58: 123-127.

40. Rowarth, J.S., Chapman, H.M., Novis, P. and Rolston, M.P. 1997. Water stress and seed yield in perennial ryegrass (*Lolium perenne* L.) grown in pots. *Journal of Applied Seed Production* 15: 89-92.

41. Rowarth, J.S., Cookson, W.R., Williams, P.H. and Cameron, K.C. 1999. Fate of nitrogen in perennial ryegrass (*Lolium perenne* L.) seed crops: can we alter destiny? *Proceedings of the International Herbage Seed Conference* 4: 91-95.

42. Sherlock, R.R. and Goh, K.M. 1985. Dynamics of ammonia volatilization from simulated urine patches and aqueous urea applied to pasture. I. Field experiments. *Fertilizer Research* 5: 181-197.

43. Smyth, A.J. and Dumanski, J. 1994. Progress towards an international framework for evaluating sustainable land management (FESLM). *15th World Congress of Soil Science, Mexico*: 373-378.

44. Stone, J.A. and Buttery, B.R. 1989. Nine forages and the aggregation of a clay loam soil. *Canadian Journal of Soil Science* 69: 165-169.

45. Syers, J.K., Hamblin, A. and Pushparajah, E. 1994. Development of indicators and thresholds for the evaluation of sustainable land management. *15th World Congress of Soil Science, Mexico*: 398-409.

46. Thomson, N.A., Roberts, A.H.C., Judd, T.G. and Clough, J.S. 1991. Maximising dairy production by using nitrogen fertilizer and calving early. *Proceedings of the New Zealand Grassland Association* 53: 85-90.

47. Williams, P.H., Rowarth, J.S. and Tregurtha, R. 1997. Effects of a perennial ryegrass (*Lolium perenne* L.) seed crop on soil nitrogen status. *Proceedings of the Agronomy Society of New Zealand* 27: 15-18.