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Review

Nutrients and Moisture Inputs for Grass Seed Yield

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ABSTRACT

The perfect soil for production of grass seed does not exist; all soils (which can be regarded as growth media) must be amended in some way to achieve optimum seed yields. Common amendments include soil nutrients (fertilisers) and, in New Zealand, soil moisture (irrigation). Some of these inputs, e.g. nitrogen and water, must be manipulated during the growing season because they are highly mobile in the soil-plant-atmosphere; their very mobility causes concern within the framework of 'sustainability'. Research on efficiency of use of inputs is in vogue, as is increased grower participation in research funding. The latter is not without problems: recipe-orientated trials and protectionism of results. This review paper integrates the research results available on fertiliser and water use in grass seed production with results from farm surveys. Future directions for research are also discussed.

Additional index words: **fertiliser, irrigation, nitrogen, ryegrass, sustainability, technology transfer.**

INTRODUCTION

Despite the fact that grasslands cover 20% of the earth's surface (Hodgson and Illius, 1996), and are grazed by animals, many of whom are then consumed by our ever-increasing population, grass seed remains a low-valued product. In our consumer-driven economy, there is increasing pressure on land in New Zealand and Europe currently used to produce grass seed, to produce high-value crops, such as vegetables, instead. On mixed cropping-animal farms, the attraction of grass-seed crops is not only in the value of the seed, but is also in the winter feed for sheep and cattle, plus the opportunity for weed control for other crops. However, the traditional mixed farm is disappearing and the onus is on the herbage seed scientist to help maximise returns from grass-seed crops to ensure they remain attractive within a crop rotation. While in other areas, such as Oregon, long-term grass seed crops have been possible because of chemical inputs and stubble burning, both practices are now regarded as unsustainable, putting an emphasis on research into 'alternative' methodology. In Europe, concern about nitrate in groundwater has resulted in restrictions on the amount of nitrogen fertiliser that can be applied, and the use of chemical sprays is strictly legislated.

Within the framework of 'sustainability', the key to maximising returns is efficient use of inputs; this review paper will focus on plant nutrition, including water, in grass seed crops.

NITROGEN

In most cropping soils, plant-available nitrogen (N) is present in insufficient quantities to allow plants to achieve maximum yields. This is not only because N is required in relatively large amounts by plants (the dry matter of a typical ryegrass plant will be between 3 and 5% N), but also because N is highly mobile within the soil-plant-atmosphere cycle. In biologically-active soils, nitrate can be measured within 2 h of urea being applied, even at temperatures of below 3°C (Sherlock, Khan, Sommer, Wood, Guertal, Freney and Cameron, 1996). Once in the nitrate form, N is subject to leaching; as the ammonium form it is subject to volatilisation.

In general, applying fertiliser N to grass seed crops (assuming that there is no greater limiting factor such as soil moisture (Rolston, Rowarth, DeFilippi and Archie, 1994)) increases tillering and dry matter production (which has implications for the type of harvesting equipment necessary), affects inflorescence determination and yield component dynamics, and ultimately increases seed yield and quality (Hebblethwaite and Ivins, 1977; Rolston *et al.*, 1994).

Research on the fertiliser N required by grass seed crops has tended to focus on rate and timing of application. Increasing fertiliser is associated with an increase in seed yield until an optimum application rate is reached (Hampton, 1988). Optimum rates vary widely in the literature, probably due to differences in soil N contribution (estimated at 39 (Hampton, 1987) to 60-105 (White, 1990) kg ha^{-1}), cropping history, soil temperature, rainfall or atmospheric inputs (estimated at 40-50 kg ha^{-1}yr^{-1} in Britain; Powlson, 1993). Furthermore, the range in maximum yields reported in the literature (Table 1) suggests that in some research N was not the major limiting factor, or the maximum response had not been reached (as in some cases the top rate of added N produced an increase in seed yield). Generalisations about optimum fertiliser-N requirements

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Table 1. Highest nitrogen fertiliser application rate producing a significant increase in grass seed yield. Range indicates that the given figures were optimum for different years or cultivars.

Species	N applied (kg ha^{-1})	Seed yield (kg ha^{-1})	Head numbers (m^2)	Author(s)	Year	Country
Agrostis tenuis	80			Brown & Archie	1986	New Zealand
	240	905	2600	Jin *et al.*	1996	New Zealand
Bromus inermis	100	613	130	Rowarth & Archie	1993	New Zealand
Dactylis glomerata	100	1260	795	Nordestgaard	1986	Denmark
	160			Ivany[1]	1984	Germany
	200			Kern & Baryla[1]	1983	Poland
Festuca arundinaceae	80	780	560	Hare & Rolston	1990	New Zealand
	60-100	1781-1217	na[2]	Young *et al.*	1990	USA
F. pratensis	100	1230	1751	Nordestgaard	1986	Denmark
F. rubra	0-80	429-221	1821-708	Hare & Archie	1990	New Zealand
	90	1260	3150	Meijer & Vreeke	1988	Netherlands
	100	1140	2762	Nordestgaard	1986	Denmark
	180			Chakurov[1]	1984	Bulgaria
Lolium multiflorum	100	1880	1498	Nordestgaard	1986	Denmark
L. perenne	60	709	na	Acikgoz & Karagoz	1989	Turkey
	60-120	1095-1378	na	Mares-Martin & Gamble	1993	Canada
	60-120	539-2038	1636-1550	Young *et al.*	1995	Oregon
	80-120	2000	2400	Hebblethwaite & Ivins	1977	Britain
	100	1400	na	Young *et al.*	1990	Oregon
	100	1118	1249	Hampton	1987	New Zealand
	120	2150	1490	Rolston *et al.*	1994	New Zealand
	130	1290	2398	Meijer & Vreeke	1988	Netherlands
	180	2240	1270	Rowarth	1997	New Zealand
Phleum pratense	100	770	884	Nordestgaard	1986	Denmark
Poa pratensis	60			Mikhailichenko & Sycheva[1]	1983	Russia
	80			Olkowski[1]	1983	Poland
	50-100	990-680	1756-2061	Nordestgaard	1986	Denmark
	120	1599	2689	Meijer & Vreeke	1988	Netherlands

[1] *Cited in Hampton, 1988*

[2] *na = data not available*

should therefore be viewed with caution.

Recognition that the traditional 'rate of fertiliser trial' approach to estimating optimum N applications is temporally and spatially specific has stimulated research on alternative methods for predicting fertiliser-N requirements (Rowarth and Archie, 1994). In New Zealand, the concentration of N in perennial ryegrass (*Lolium perenne* L.) cut just before stem elongation (early spring) is related to seed yield at harvest and maximum seed yields (*ceteris paribus*) can be achieved with a herbage N concentration of 5-6% (Rowarth and Archie, 1994, 1995). For cocksfoot (*Dactylis glomerata* L.), 3.75% is thought to be optimal (Schöberlein and Wahl, 1993). Determining plant-N status in early spring allows seed growers time to correct deficiencies by applying fertiliser-N, and assists them to avoid over- or under-application. This strategy is also conducive to high nitrogen-use efficiency.

Optimum response to N is thought to be achieved by applying fertiliser between spikelet initiation (Hampton, 1987) and stem elongation (Brown, 1980a). Delaying application in spring tends to reduce the number of fertile tillers, which is often related to a decrease in seed yield (Nordestgaard, 1986). The balance between autumn and spring application has also received attention in the literature, and, again, recommendations vary. In general, seed yields in Scandinavia and Europe have been shown to increase when fertiliser-N is applied one third in autumn and two thirds in early spring (Nordestgaard, 1986; Meijer and Vreeke, 1988). However, in New Zealand a single spring application has been found to be sufficient (Hampton, 1987). Research is now under way using ^{15}N to establish the contribution of different timings of N application to final seed yield, and the fate of that not taken up by the plant (Rowarth, unpubl. data).

Seed yield component responses to increasing N have been attributed to increases in: head size (Langer, 1959), spikelets per tiller (Ryle, 1964; Hill and Watkin, 1975; Hare and Rolston, 1990; Mares Martins and Gamble, 1993), florets per spikelet (Ryle, 1963; Hare and Rolston, 1990; Young, Chilcote and Youngberg, 1995) and seeds per head (Brown and Archie, 1986; Young *et al.*, 1995). Spring N generally does not have a positive effect on seed head numbers (exceptions are Rolston *et al.*, 1994; Young *et al.*, 1995), probably because by the time it is applied, most of the tillers that are of sufficient size to produce a seed head by the traditional harvest date have already become reproductive. Those that are stimulated by N fertiliser to increase in size and become reproductive will not be sufficiently mature to contribute to harvest. Applying fertiliser after stem elongation decreases seed yield (Hebblethwaite and Ivins, 1978) and, particularly in an N-deficient crop where there is little competition for light, stimulates secondary tillers (Meijer and Vreeke, 1988) that can cause harvesting difficulties by preventing drying of the crop and by adding to the 'bulk' to be processed. However, late-spring N can increase thousand seed weight and number of seeds per fertile tiller (Nordestgaard, 1986). Differences in reported responses in components of yield to added N probably reflect the fact that crops were at different developmental stages (physiological age) when the fertiliser-N was added.

Although increased N-use has increased seed yields and decreased the incidence of blind seed disease (Hampton and Scott, 1980a,b; DeFilippi, Hampton, Rolston and Rowarth, 1996), concerns about environmental contamination, particularly of drinking water, have also increased. This has resulted in an increased emphasis on fertiliser recovery efficiency. In general, N recovery decreases as N application increases, but time of application has a large effect on efficiency of uptake. Studies in ryegrass in New Zealand (Williams, Rowarth and Tregurtha, 1997) have shown that of 120 kg ha^{-1} N applied in spring, 10% was recovered in the seed and 30% in the herbage; the remainder was found in the soil within the rooting zone. When N was applied during autumn (30 kg ha^{-1}) plus winter (60 kg ha^{-1}), plus at spikelet initiation (60 kg ha^{-1}) plus at stem elongation (60 kg ha^{-1}) yields were over 2000 kg ha^{-1}, apparent nitrogen recovery (ANR; Kanneganti and Klausner, 1994) was 68% and 52 kg ha^{-1} of N was removed in the seed (Rowarth, unpubl. data). This strategy clearly matches N demand by the plant (Scharrer and Mengel, 1960) and results in maximum uptake of applied N. In contrast, applying the N as 30 kg ha^{-1} in autumn and 180 kg ha^{-1} at spikelet initiation gave a yield of 1930 kg ha^{-1}, but an ANR of only 31%. In browntop (*Agrostis capillaris* L.) ANR over the growing season averaged 60, 69 and 50% at 60, 120, and 240 kg ha^{-1} N respectively (Jin, Rowarth, Scott and Sedcole, 1996).

Seed quality is yet another consideration in the application of N. Seed N content has been reported to be correlated with germination rate and seedling dry weight in perennial ryegrass (Ene and Bean, 1975; Bean, 1980). In most grasses, increasing N application to the mother plant can increase TSW and hence seedling vigour (Bean, 1980). Effects of seed N concentration on seed vigour have not been reported recently. This may reflect adherence to ISTA (1993) recommendations (addition of 0.2% potassium nitrate) to break seed dormancy when measuring germination. In cereals exogenous nitrate can infiltrate the seed and increase germination and seedling vigour by influencing seed water uptake and the mobilisation of seed reserves (Andrews, Lieffering and McKenzie 1994; Andrews, Lieffering, McKenzie and Jones, 1995). Thus the effects on the seed (germination and vigour) of differences in N application to the mother plant may be obscured.

PHOSPHORUS

Phosphorus (P) is not usually leached from soil, does not volatilise, and is immobilised only slowly during winter; as a consequence phosphate concentration can be ameliorated before the growing season. In New Zealand, P is usually added in the form of a compound fertiliser at

Table 2. Timing of nitrogen applications which resulted in significant increases in grass seed yield.

Species	Timing of N application	Seed yield (kg ha^{-1})	Head numbers (m^{2})	Author(s)	Year
Agrostis tenuis	late spring	209-437	5300-7100	Brown & Archie	1986
Bromus inermis	insensitive	312-613	na-130	Rowarth & Archie	1993
B. wildenowii	stem elongation	4000	na[1]	Hare *et al.*	1989
Dactylis glomerata	autumn plus early spring	1260	795	Nordestgaard	1986
Festuca arundinaceae	insensitive	862	468	Hare & Rolston	1990
F. rubra	autumn plus early spring	1140	2762	Nordestgaard	1986
	insensitive	429-221	1821-708	Hare & Archie	1990
L. x hybridum	insensitive	na	na	Brown	1980
Lolium multiflorum	autumn and mid spring	1880	1498	Nordestgaard	1986
	autumn plus after floret initiation	na	na	Brown	1980
L. perenne	all at spikelet initiation	699-1118	1036-1249	Hampton	1987
	all at stem elongation	1135	2400	Brown	1980
	before stem elongation	na	2000	Hebblethwaite & Ivins	1978
	autumn and very early spring	1236	2873	Hill	1970
Phleum pratense	mid spring	790	836	Nordestgaard	1986
Poa pratense	autumn and early spring	990-680	1756-2061	Nordestgaard	1986

[1] *na = data not available*

drilling. However, P concentrations (measured as Olsen P in μgml^{-1}) are often higher than might be considered necessary, due to crop requirements in other parts of the rotation. Olsen P values of above 15 are recommended and are associated with ryegrass seed yields of more than 2000 kg ha^{-1}. Although an Olsen P of 6 μgml^{-1} has been reported to be adequate (Brown, 1980b), the yield of only 1000 kg ha^{-1} ryegrass seed indicates that P was not the major limiting factor in the trial. In Oregon, a Bray P of over 25 μgg^{-1} is recommended (Horneck and Hart, 1988).

Phosphorus is important in seedling vigour; Italian ryegrass seed with high P concentrations produced larger seedlings that developed roots more rapidly than seed with low P concentration (Kemp and Blair, 1994). This effect has also been reported in wheat (Bolland, Riley, Thomson, Paynter and Baker, 1990). This will confer an advantage in terms of subsequent P nutrition of the seedlings because, as already noted, P is relatively immobile in soil.

SULPHUR

Sulphur (S) is generally managed in the same way as P, except where very early N is applied as ammonium nitrate and where late N is applied as ammonium sulphate. In these cases very high sulphate concentrations (e.g. 123 μgg^{-1} MAF quick test; Cornforth and Sinclair, 1984) in the soil have been noted, but they have not been associated with correspondingly high yields. A preliminary study (Rowarth and Archie, unpubl. data) has indicated that a ryegrass herbage S of 4% before stem elongation will give maximum yields. In Oregon the recommendation is to apply sulphur early in the season (Hart, Horneck, Peek and Young, 1989).

CALCIUM

Liming to maintain soil at a pH optimum for nutrient availability and biological N fixation (where appropriate) involves application of calcium carbonate. As a consequence, calcium is not generally deficient in cropping soils. However, it is known that seeds that are low or deficient in calcium have poor germination and produce abnormal, low vigour seedlings, even though they may be able to germinate successfully in a complete nutrient medium (Welch, 1986).

POTASSIUM

On recent soils, which are releasing potassium (K) from clay minerals, a potassium response is rare, particularly when compound fertilisers are used as part of the normal fertilisation during the rotation. New Zealand cropping soils generally contain 120-480 μgg^{-1} soil exchangeable K (New Zealand Soil Bureau, 1968), and no response to K has been recorded (Brown, 1980; Rowarth, 1992). In Oregon it is recommended that the soil contain at least 100 μgg^{-1} soil exchangeable K (Hart, Horneck, Young and Silberstein, 1990; Horneck, Hart and Young, 1993).

TRACE ELEMENTS

Trace element deficiencies in grass seed crops have not been reported.

WATER

Water can be regarded as a nutrient as it is a constituent within the photosynthetic reaction (Mengel and Kirkby, 1987). However, it also fulfils many other functions within the plant: support, nutrient uptake and transport, as well as being a medium for biochemical reactions. A water loss of 10-15% can markedly affect plant metabolic processes, reducing cell growth, cell wall and protein synthesis, and nitrate reductase activity, increasing abscisic acid and closing stomata, which results in a decrease in photosynthesis (Hsaio, Acevedo, Fereres and Henderson, 1976). These effects occur before there are any visible signs of wilting and will affect the leaf area of a plant, the maintenance of which throughout the growing season is of importance for seed yield (Lorenzetti, 1993).

Lack of water is a major limitation in crop yield around the world (Larcher, 1995) but irrigation requirements of grass-seed crops have received little attention. This is probably because most major ryegrass seed growing areas are on heavy soils and have reliable spring rain. In New Zealand many crops are grown on soils with low water holding capacity and over 50% are irrigated to some extent (Rolston *et al.*, 1994). The lack of research may reflect the relatively low value of grass seed and the high capital and operating costs of irrigation.

In general, moisture stress shortens the period of reproductive development and decreases seed yield (Lambert, 1967; Hebblethwaite, 1977; Rolston *et al.*, 1994). Early moisture stress (before or during stem elongation) in ryegrass decreases the number of reproductive heads, which in turn decreases seed yield (Hebblethwaite, 1977; Rowarth, Chapman, Novis and Rolston, 1997). A soil water deficit of less than 100 mm developing after stem elongation has little effect on floret site utilisation (FSU; Hebblethwaite, 1977) and seed yields of over 2000 kg ha^{-1} can be obtained (Rolston *et al.*, 1994). However, a moisture deficit greater than 100 mm on a light soil reduced FSU and prevented response to nitrogen (Rolston *et al.*, 1994). On heavy soils, irrigation increased yields by 38-53% where soil moisture deficits reached 330 mm by harvest, but not where they reached 180 mm (Rowarth unpubl. data). Moisture stress at anthesis decreases seed set (and, hence, seed yield), possibly because the photoassimilate supply, which is vital to the developing ovule, is reduced due to a decrease in photosynthesis, and because the pollen tube and stigmatic surface is sensitive to desiccation (Rowarth *et al.*, 1997). Moisture stress after anthesis decreases thousand seed weight (Lambert, 1967), probably because leaf area and photosynthetic capacity are reduced. Excess water, however, can increase vegetative tillers (Hebblethwaite, 1980) which are a stronger assimilate sink than reproductive tillers; assimilate partitioned away from developing seeds results in increased abortion and decreased seed yields (Griffith, 1992). Furthermore, these vegetative tillers create harvesting difficulties - not only do they retain moisture that inhibits seed drying, but also they can grow through the cut crop making combining extremely difficult.

Water requirements increase with increased nitrogen supply as the latter increases herbage production. Water use between head emergence and harvest was 40% more on high N plots (150 kg ha^{-1} at spikelet initiation) than control plots (Cookson, Rowarth and Cameron, 1997). A decrease in transpiration was measured on control plots *cf.* high N plots, which was associated with a decrease in photosynthesis (Hsaio *et al.*, 1976). However, although total water use increased, water-use efficiency was also increased, i.e. yields from high N plots were more than 40% greater than from control plots.

Irrigation may also increase thousand seed weight (Ene and Bean, 1975), which, within a seed lot, is associated with increased seedling vigour (Brown, 1977).

Further research to define what constitutes moisture stress in herbage seed production and how it varies with species and developmental stage is necessary.

FUTURE DIRECTIONS

As adumbrated in the introduction, there are increasing opportunities for the seed grower to choose more lucrative options for production than herbage seed. This imposes increasing pressures on seed scientists to find ways of decreasing costs of inputs while maximising outputs. All this is within an environment of sustainability issues, and public demands for quality products. Research, with an emphasis on efficiency of inputs, will become increasingly necessary.

There are, however, a number of constraints which must first be overcome:

1. In identifying areas for research, growers are more interested in 'how' than 'why'. Ideally they would like a recipe for their farming practices on their soil type and with their machinery that will guarantee them top yields. This puts the emphasis back on trials which are temporally and spatially specific - an approach unlikely to improve understanding of the agronomy and physiology of seed production.
2. Funding is increasingly allocated on a single-year basis, encouraging the type of research with guaranteed short-term outcomes. Sustainable-land management cannot be judged in the short term.
3. Research funded by growers is understandably regarded by the growers as their own. Commercial advantages mean that publication in the public arena is precluded; indeed, seed scientists are regarded as commercially sensitive property. This encourages inbreeding and isolation of ideas at a time when interchange of ideas is increasingly important.

Overcoming these constraints is certainly a challenge for seed scientists, particularly the requirements of continuing to produce economically viable seed yields without degradation of either soil or water quality. Within the framework of sustainable-land-management, we need to show growers (and politicians), the importance of scientific rather than recipe-orientated research. We also need them to understand that the problems facing them are not unique - the same problems are faced by seed growers all over the world and can be solved more quickly by all of us working together.

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REFERENCES

1. Acikogoz, E. and Karagoz A. 1989. Effect of row spacing, seeding rate and nitrogen fertilization on seed yield of perennial ryegrass under dryland conditions. *Journal of Applied Seed Production* 7: 50-52.
2. Andrews, M., Lieffering, M. and McKenzie, B.A. 1994. Nitrate effects on mobilisation of seed reserves in temperate cereals. In: Seed symposium: seed development and germination. *Agronomy Society of New Zealand Special Publication* No. 9: 43-47.
3. Andrews, M., Lieffering, M., McKenzie, B.A. and Jones, A.V. 1995. Applied nitrogen and seed nitrogen effects on growth of barley (*Hordeum vulgare* L.) seedlings prior to emergence: importance of water uptake. *Proceedings of the Agronomy Society of New Zealand* 25: 1-6.
4. Bean, E.W. 1980. Factors affecting the quality of herbage seeds. In: Seed Production (ed. P. D. Hebblethwaite), 593-604, Butterworths, London.
5. Bolland, M., Riley, M., Thomson, B., Paynter, B. and Baker, M. 1990. Seed phosphorus - its effect on plant production. *Western Australian Journal of Agriculture* 31: 20-22.
6. Brown, K.R. 1977. Parent seed weight, plant growth, and seeding in 'Grasslands Tama' Westerwolds ryegrass. *New Zealand Journal of Experimental Agriculture* 5: 143-146.
7. Brown, K.R. 1980a. Recent grass seed production studies in Canterbury. In: Herbage Seed Production (ed. J.A. Lancashire), 12-14, Grassland Research and Practice Series No. 1., New Zealand Grassland Association.
8. Brown, K.R. 1980b. Seed production in New Zealand ryegrasses. *New Zealand Journal of Experimental Agriculture* 8: 33-39.
9. Brown, K.R. and Archie, W.J. 1986. Effect of nitrogen application on seed production of 'Grasslands Egmont' and 'Grasslands Sefton' browntops (*Agrostis capillaris*). *New Zealand Journal of Experimental Agriculture* 14: 257-260.

10. Cookson, W.R., Rowarth, J.S. and Cameron, K.C. 1997. Effect of nitrogen fertiliser on the irrigation requirements of perennial ryegrass (*Lolium perenne* L.) seed crop. *Journal of Applied Seed Production* 15: 95-98

11. Corkill and Rumball, W. 1980. Problems of amenity grass seed production in New Zealand. In: Herbage Seed Production (ed. J.A. Lancashire), 26-30, Grassland Research and Practice Series No. 1., New Zealand Grassland Association.

12. Cornforth, I.S. and Sinclair, A.G. 1984. Fertiliser recommendations for pasture and crops in New Zealand. Ministry of Agriculture and Fisheries, Private Bag, Wellington, New Zealand. 66p.

13. DeFilippi, J.M., Hampton, J.G., Rolston, M.P. and Rowarth, J.S. 1996. Effect of nitrogen and irrigation on blind seed disease in perennial ryegrass (*Lolium perenne* L.) cv. Grasslands Nui. *Journal of Applied Seed Production* 14: 81-83.

14. Ene, B.N. and Bean, E.W. 1975. Variations in seed quality between certified seed lots of perennial ryegrass and their relationship to nitrogen supply and moisture status during seed development. *Journal of the British Grassland Society* 30: 195-199.

15. Griffith, S.M. 1992. Changes in post-anthesis assimilates in stem and spike components of Italian ryegrass (*Lolium multiflorum* Lam.) I. Water soluble carbohydrates. *Annals of Botany* 69: 243-248.

16. 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.

17. Hampton, J.G. 1988. Herbage seed production. *Advances in Research and Technology of Seeds* 11: 1-28.

18. Hampton, J.G. and Scott, D.J. 1980a. Blind seed disease of ryegrass in New Zealand. I. Occurrence and evidence for the use of nitrogen as a control measure. *New Zealand Journal of Agricultural Research* 23: 143-147.

19. Hampton, J.G. and Scott, D.J. 1980b. Blind seed disease of ryegrass in New Zealand. II. Nitrogen fertiliser: effect on incidence and possible mode of action. *New Zealand Journal of Agricultural Research* 23:149-153.

20. Hare, M.D. and Archie, W.J. 1990. Red fescue seed production: post-harvest management, nitrogen and closing date. *Proceedings of the New Zealand Grassland Association* 52: 81-85.

21. Hare, M.D. and Rolston, M.P. 1990. Nitrogen effects on tall fescue seed production. *Journal of Applied Seed Production* 8: 28-32.

22. Hare, M.D., Brown, K.R., Archie, W.J. and Rolston, M.P. 1989. Seed production of prairie grass. I. Effect of sowing method and time of nitrogen application. *Journal of Applied Seed Production* 7: 61-64.

23. Hart, J.M., Horneck, D.A., Peek, D. and Young, W.C. III. 1989. Nitrogen and sulfur uptake for cool season forage and turf grass grown for seed. In: Seed production Research at Oregon State University: USDA-ARS cooperating (ed. W.C. Young III), 15-16, Oregon State University, Corvallis.

24. Hart, J.M., Horneck, D.A., Young, W.C. III and Silberstein, T.B. 1990. Potassium for grass seed production. In: Seed Production Research at Oregon State University: USDA-ARS cooperating (ed. W.C. Young III), 13-14, Oregon State University, Corvallis.

25. Hebblethwaite, P.D. 1977. Irrigation and nitrogen studies in S23 ryegrass grown for seed 1. Growth, development, seed yield components and seed yield. *Journal of Agricultural Science, Cambridge* 88: 605-614.

26. Hebblethwaite, P.D. 1980. Seed Production. Butterworths, London-Boston, 694pp.

27. Hebblethwaite, P.D. and Ivins, J.D. 1977. Nitrogen studies in *Lolium perenne* grown for seed I. Level of application. *Journal of the British Grassland Society* 32: 195-204.

28. Hebblethwaite, P.D. and Ivins, J.D. 1978. Nitrogen studies in *Lolium perenne* grown for seed II. Timing of nitrogen application. *Journal of the British Grassland Society* 33: 159-166.

29. Hill, M.J. 1970. Ryegrass seed crop management. *New Zealand Journal of Agriculture* 121: 52-54.

30. Hill, M.J. and Watkin, B.R. 1975. Seed production studies on perennial ryegrass, timothy and prairie grass. *Journal of the British Grassland Society* 30: 63-71.

31. Hodgson, J. and Illius, A.W. 1996. The Ecology and Management of Grazing Systems. CAB International, Oxford. pp 466.

32. Horneck, D.A. and Hart, J.M. 1988. A survey of nutrient uptake and soil test values in perennial ryegrass and turf type tall fescue fields in the Willamette Valley. In: Seed Production at Oregon State University: USDA-ARS cooperating (eds. H.W. Youngberg and J. Burcham), 13-14, Oregon State University, Corvallis.

33. Horneck, D.A., Hart, J.M. and Young, W.C. III. 1993. Effect of soil K on perennial ryegrass and tall fescue. In: Seed Production Research at Oregon State University: USDA-ARS cooperating (ed. W.C. Young III), 14-17, Oregon State University, Corvallis.

34. Hsaio, T.C., Acevedo, E., Fereres, E. and Henderson, D.W. 1976. Water stress, growth and osmotic adjustment. *Philosophical Transactions of the Royal*

Society London 273: 479-500.

35. ISTA. 1993. International rules for seed testing. *Supplement to Seed Science and Technology* 21: 1-288.

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

37. Kanneganti, V.R. and Klausner, S.D. 1994. Nitrogen recovery by orchard grass from dairy manure applied with or without fertilizer nitrogen. *Communication in Soil Science and Plant Analysis* 25: 2771-2783.

38. Kemp, P.D. and Blair, L. 1994. Phosphorus efficiency in pasture species. VII. Ontogeny, growth, acquisition and P utilisation of Italian ryegrass under P deficient and P sufficient conditions. *Australian Journal of Agricultural Research* 45: 669-688.

39. Lambert, D.A. 1967. The effects of nitrogen and irrigation on timothy (*Phleum pratense*) grown for production of seed. *Journal of Agricultural Science, Cambridge* 69: 231-239.

40. Langer, R.H.M. 1959. Growth and nutrition of timothy (*Phleum pratense*) grown for production of seed. IV. Growth and flowering at different levels of nitrogen. *Annals of Applied Biology* 47: 740-751.

41. Larcher, W. 1995. Natural environmental constraints. In: Physiological Plant Ecology, 321-448, Springer, Berlin.

42. Lorenzetti, F. 1993. Achieving potential seed yields in species of temperate regions. *Proceedings of the XVII International Grassland Congress*: 1621-1628.

43. Mares Martin, V.M. and Gamble, E.E. 1993. Responses of two perennial ryegrass cultivars grown for seed to nitrogen, paclobutrazol and propiconazole. *Journal of Applied Seed Production* 11: 64-72.

44. Meijer, V.J.M. and Vreeke, S. 1988. Nitrogen fertilisation of grass seed crops as related to soil mineral nitrogen. *Netherlands Journal of Agricultural Science* 36: 375-385.

45. Mengel, K. and Kirkby, E.A. 1987. Nutrient uptake and assimilation. In: Principles of Plant Nutrition, 113-191, International Potash Institute, Bern.

46. New Zealand Soil Bureau. 1968. Soils of New Zealand part 2. Soil Bureau Bulletin 26 (2), New Zealand Department of Scientific and Industrial Research, Wellington. 220 p.

47. Nordestgaard, A. 1986. Investigations on the interaction between level of nitrogen application in the autumn and time of nitrogen application in the spring to various grasses. *Journal of Applied Seed Production* 4: 16-25.

48. Powlson, D.S. 1993. Understanding the nitrogen cycle. *Soil Use and Management* 9: 86-94.

49. 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: 92-94.

50. Rowarth, J.S. 1992. Ryegrass nutrient and seed yield survey. *New Zealand Herbage Seed Subsection of Federated Farmers Newsletter* 5: 5.

51. Rowarth, J.S. and Archie, W.J. 1993. Reproductive initiation, closing dates, nitrogen requirements and harvesting of smooth brome cv. Grasslands Tiki. *Proceedings of the XVII International Grassland Congress:* 1674-1675.

52. Rowarth, J.S. and Archie, W.J. 1994. The nutrient needs of small seed crops: a new concept in optimising seed yields. *Proceedings of the Agronomy Society of New Zealand* 24: 87-89.

53. Rowarth, J.S. and Archie, W.J. 1995. A diagnostic method for prediction of seed yield in perennial ryegrass. *Proceedings of the International Herbage Seed Conference* 3: 64-67.

54. 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

55. Ryle, G.J.A. 1963. Studies in the physiology of flowering of timothy (*Phleum pratense* L.). IV. Effects of shoot age and nitrogen level on size of inflorescence. *Annals of Botany* 27: 437-479.

56. Ryle, G.J.A. 1964. The influence of date of origin of the shoot and level of nitrogen on ear size in three perennial grasses. *Annals of Applied Biology* 53: 311-323.

57. Scharrer, K. and Mengel, K. 1960. On the transient occurrence of visible magnesium deficiency in oats. *Agrochimica* 4: 3-24.

58. Sherlock, R.R., Khan, R.Z., Sommer, S., Wood, C.W., Guertal, E.A., Freney, J.R., and Cameron, K.C. 1996. Nitrous oxide and methane fluxes from piggery effluent applied to pasture soil. *Proceedings of the Australian Soil Science Society and New Zealand Soil Science Society National Soils Conference* 3: 231-232.

59. Schöberlein, W. and Wahl, H.J. 1993. Efficient nitrogen fertilisation in grass seed crops with regard to soil mineral nitrogen content and analysing grass tillers in spring. *Proceedings of the XVII International Grassland Congress* 1695-1696.

60. Welch, R.M. 1986. Effects of nutrient deficiencies on seed production and quality. In: Advances in Plant Nutrition (ed. P.B. Tinker and A. Lauchli), Vol. 2. Praeger, New York.

61. White, J.G.H. 1990. Herbage seed production. In: Pastures (ed. R.H.M. Langer) 370-408, Oxford

University Press, Auckland.

62. Williams, P.H., Rowarth, J.S., 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: in press.
63. Young, W.C. III., Silberstein, T.B. and Hart, M.J. 1990. Nitrogen fertilizer requirements for grass seed production in non-burn post-harvest residue management systems. In: Seed production research at Oregon State University - USDA-ARS cooperating (ed. W.C. Young III.), 12-13, Department of Crop and Soil Science Ext/CrS 83 4/91.
64. Young, W.C. III., Chilcote, D.O. and Youngberg, H.W. 1995. Seed yield responses of perennial ryegrass to spring applied nitrogen at different rates of paclobutrazol. *Journal of Applied Seed Production* 13: 10-15.