NUTRIENTS AND MOISTURE INPUTS FOR GRASS SEED YIELD

J.S. Rowarth
Plant Science, PO Box 84, Lincoln University, Canterbury, New Zealand

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 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 are technology-transfer programmes taking research results direct to the grower in their own environment. However, increased grower participation in research funding 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. Technology transfer, sustainability and future directions for research are discussed.

KEYWORDS

Fertilisers, 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 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 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 that they are attractive within a crop rotation. 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.

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.

NITROGEN (N)

In most cropping soils plant-available 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 urea can be converted into nitrate within 2 h of being applied, even at temperatures of below 3 °C (R. Sherlock, Lincoln University, pers. comm., 1995). 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 seed crops (assuming that there is no greater limiting factor such as soil moisture (Rolston et al., 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 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 is reached (Hampton 1988). Optimum rates vary widely in the literature, probably due to differences in soil N contribution (estimated at 30 (Hampton, 1987) to 60-105 (White, 1990) kg/ha), cropping history, soil temperature, rainfall or atmospheric inputs (estimated at 40-50 kg/ha/yr in Britain (S. Jarvis, North Wyke, pers. comm., 1995)). Furthermore, the range in maximum yields reported in the literature (e.g., 500-2150 kg/ha for perennial ryegrass) suggests that in some reports N was not the major limiting factor or (as in some cases, the top rate of N addition produced an increase in seed yield) the maximum response had not been reached. Generalisations about optimum fertiliser-N requirements 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 ryegrass 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 glomeratum*), 3.75 % is thought to be optimum (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 (Rowarth, Knox, Rolston and Archie, in prep.)

Optimum response to N is thought to be achieved by applying fertiliser between spikelet initiation (Hampton, 1987) and stem elongation (Brown, 1980). However, recent research (Rowarth unpublished) indicates that N deficiency in the period from vegetative (winter) to spikelet initiation will also restrict seed yield. Delaying application in spring tends to reduce number of fertile tillers which is often related to a decrease in seed yield (Nordestgaard, I986). 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 respond to fertiliser-N 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 (Cookson, Cameron and Rowarth, unpubl.).

Seed yield component responses to increasing N have been attributed to increases in every component: increasing 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 et al., 1995) and increased seeds per head (Brown and Archie, 1986; Young et al., 1995). Spring N does not generally 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) which can cause harvesting difficulties. 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 use of N has increased seed yields and decreased incidence of blind seed disease (Hampton and Scott, 1980a,b; DeFilippi et al., 1996), concerns about environmental contamination, particularly of drinking water, have also increased. This has resulted in 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 et al., 1997) have shown that of 120 kg/ha 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. Further studies, also in ryegrass (Rowarth, Knox, Rolston and Archie, in prep), have shown that N application during autumn (30 kg/ha) and winter (60 kg/ha), at spikelet initiation (60 kg/ha) and at stem elongation (60 kg/ha) can result in yields of over 2000 kg/ha; apparent nitrogen recovery (ANR; Kanneganti and Klausner, 1994) was 68 %; 52 kg/ha was removed in the seed. 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 in autumn and 180 kg/ha at spikelet initiation gave a yield of 1930 kg/ha 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, respectively (Rowarth et al., 1995; Jin et al., 1996).

Seed quality is yet another consideration in the application of N. Seed N content has been reported to be significantly 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) when measuring germination. In cereals it has been found that exogenous nitrate can infiltrate the seed and increase germination and seedling vigour by influencing seed water uptake and the mobilisation of seed reserves (Andrews et al., 1994, 1995). Thus the effects on the seed of differences in N applications to the mother plant are obscured (Bennett, Rowarth and Jin, 1998). For instance, without chilling or the addition of potassium nitrate, seedling vigour (as measured by accelerated ageing followed by germination) in high N (2.6 %) perennial ryegrass seed was 50 % higher than low N (1.85 %) ryegrass seed. The addition of potassium nitrate reduced this difference to 30 % and chilling removed it completely. Similarly, browntop germination was 44, 52, 59 and 76 % at 0, 60, 120 and 240 kg/ha N, respectively. When germinations were done according to ISTA recommendations, all were 94-95 %.

PHOSPHORUS

Phosphorus (P) is not usually leached from soil and does not volatilise; 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 drilling. However, P concentrations (measured as Olsen P in ug/ml;) 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. Although an Olsen P of 6 ug/ml has been reported to be adequate (Brown, 1980), the yield of only 1000 kg/ha ryegrass seed indicates that P was not the major limiting factor in the trial. In Oregon a Bray P of over 25 ug/g is recommended (Horneck and Hart, 1988).

Phosphorus is important in seed vigour; Italian ryegrass seed with high P concentrations produces larger seedlings which develop roots more rapidly than seed with low P concentration (Kemp and Blair, 1994); this effect has also been reported in wheat (Bolland et al., 1990) This will confer an advantage in terms of subsequent P nutrition of the seedlings because, as already noted, P is relatively immobile in soils

SULPHUR

Sulphur (S) is generally managed in the same way as P, except where very early N is applied as ammonium sulphate nitrate and where late N is applied as ammonium sulphate. In these cases very high sulphate concentrations (e.g., 123 ug/g 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, unpublished) has indicated that a herbage S of 4 % before stem elongation will give maximum yields. In Oregon the recommendation is to apply sulphur early in the season (Hart et al., 1989)

CALCIUM

Calcium is not generally deficient in cropping soils as liming to maintain soil at a pH optimum for nutrient availability and biological N fixation (where appropriate) involves application of calcium carbonate. However, it is known that seeds which 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. Thus no response to K has been recorded in New Zealand (Brown, 1980; Rowarth, 1992). In Oregon it is recommended that the soil contain at least 100 ug/g exchangeable K (Hart et al., 1990; Horneck et al., 1993).

TRACE ELEMENTS

Trace element deficiencies in grass seed crops have not been reported. In New Zealand low copper, manganese and zinc concentrations in the soil have been associated with over-liming.

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 et al., 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, probably because the major ryegrass seed growing areas are on heavy soils and have reliable spring rain. In New Zealand many crops are grown on light soils and are irrigated to some extent. 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 et al., 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 can be obtained (Rolston et al., 1994). However, moisture deficit greater than 100 mm on a light soil does reduce FSU and prevents response to nitrogen (Rolston et al., 1994). On heavy soils irrigation has been found to increase yields by 38-53 % where soil moisture deficits had reached 330 mm by harvest, but not where they reached only 180 mm (Rowarth, Rolston and Archie, unpubl.). Moisture stress at anthesis decreases seed yields (Rowarth et al., 1997), 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 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, inhibiting seed drying, but also they can grow through the cut crop.

Water requirements increase with increased nitrogen supply if it increases herbage production, but are difficult to measure in a traditional nitrogen x irrigation trial. Recent research using lysimeters (Cookson et al., 1997) has shown that water use between head emergence and harvest was 40 % more on high N plots (150 kg/ha at spikelet initiation) than control plots. A decrease in transpiration was measured on control plots *cf*. high N plots, which is 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 also increases seed quality, particularly thousand seed weight (Ene and Bean, 1975), which is, in turn, 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, particularly in the present environment of ‘climate change’.

TECHNOLOGY TRANSFER

Conclusions from research reported in the scientific literature are of little use to the seed grower unless they are provided in such a way that the seed grower can put them into practice. Surveys of practices and associated yields can provide a useful way either of making recommendations (e.g., Horneck and Hart, 1988) or of identifying problems which can then be the basis of research (Guy et al., 1990; Rowarth et al., 1993). Working with growers on a one-to-one basis within a commercial crop provides the ideal mechanism for information transfer and usually results in increased yields within the growing season (Rowarth et al., 1993). Discussion groups can also be beneficial; ‘Ryegrass 2000’ increased average seed yields by 25 % for participating farmers (Rolston, 1995).

In New Zealand an industry-funded body, the Foundation for Arable Research (FAR), has been created especially for the purpose of solving present and future problems for the grower (Pyke, 1996), taking the information generated from research to the grower through field days, seminars, reports, fact-sheets, newsletters and the press. Notwithstanding the benefits of grower-funded research and direct technology transfer, there are two major problems with this approach that have yet to be overcome. Firstly, in identifying areas for research growers are more interested in ‘how’ than ‘why’. Ideally they would like a recipe for their farming practice on their soil type and with their machinery that will guarantee them top yields. This puts an emphasis on trials which are temporally and spatially specific; this approach is unlikely to improve our understanding of the agronomy and physiology of seed production. Furthermore, funding is rarely promised for more than one year at a time, encouraging the type of research with guaranteed short-term outcomes. Sustainable-land- management cannot be judged in the short term. Secondly, research done with grower funding is regarded by the growers as their own. Wanting the commercial advantage they are against publication in the public arena; indeed, they regard seed scientists as commercially-sensitive property. This encourages isolation and inbreeding of ideas - what we and the world need is hybrid vigour from interchange of ideas.

SUSTAINABILITY

The concept of ‘sustainability’ and what exactly it defines has been the subject of many debates, papers, workshops and conferences; people are still arguing and definitions tend to reflect the bias of the definer (Syers et al., 1994). However, consensus of thought is that sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns; the five requirements (Smyth and Dumanski, 1994), occurring simultaneously, are 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

It is a tall order for an individual scientist, requiring expertise in soils, plants, insects, animals, atmosphere, economics and social sciences. It would probably help to be a philosopher as well. Clearly, sustainability issues must be addressed by teams of scientists, working together to assess the impacts of their actions and defining what is or is not acceptable. Selecting environmental indicators which will help us assess sustainable-land-management is a challenge for the future (Cornforth, 1997); our success will be judged by our grandchildren.

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, which imposes increasing pressures on the 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 product. Research with an emphasis on efficiency of inputs will become increasingly necessary. At the same time, we need fundamental research on such questions as ‘what is seed vigour?’ in order to be able to improve quality of our product. Technological barriers to trade are becoming more common; we must be ready to overcome them. While seed growers try and maximise on-farm profits, and politicians try and maximise their Balance of Trade, we, the scientists, must take the global approach.

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; in a broader context they are faced by primary producers all over the world. The problems that we face can be solved more quickly by all of us working together to improve the future of our home - “the planet Earth”.

ACKNOWLEDGEMENTS

My thanks to the Stapledon Memorial Trust for the award of a Travelling Fellowship, and to Professor Ian Cornforth, Lincoln University and Dr Phil Rolston, AgResearch Lincoln, for helpful comments.

REFERENCES

Andrews, M., M. Lieffering and B.A. McKenzie. 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.

Andrews, M., M. Lieffering, B.A. McKenzie and A.V. Jones. 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.

Bean, E.W. 1980. Factors affecting the quality of herbage seeds. Pages 593-604 *in* P.D. Hebblethwaite, ed. Seed Production Butterworths, London.

Bennett, J., J.S. Rowarth and Q.F. Jin. 1997. Potassium nitrate and seed vigour. Journal of Applied Seed Production **15:** accepted.

Bolland, M., M. Riley, B. Thomson, B. Paynter and M. Baker. 1990. Seed phosphorus - its effect on plant production. Western Australian Journal of Agriculture **31:** 20-22.

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.

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

Brown, K.R. and W.J. Archie. 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.

Cookson, W.R., J.S. Rowarth and K.C. Cameron. 1997. Water use efficiency in perennial ryegrass (*Lolium perenne* L.). Journal of Applied Seed Production **15:** in press

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

Cornforth, I.S. 1997. Selecting indicators for assessing land management. *in* ed S. Swaffield. Sustainability. Lincoln University Press, Canterbury, New Zealand. in press

DeFilippi, J.M., J.G. Hampton, M.P. Rolston and J.S. Rowarth. 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.

Ene, B.N. and E.W. Bean. 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 Grasslands Society **30:** 195-199.

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.

Guy, B.R., W.J. Archie and J.S. Rowarth. 1990. Browntop seed production: past, present and future. Proceedings of the New Zealand Grassland Association **52:** 87-89.

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.

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

Hampton, J.G. and D.J. Scott. 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.

Hampton, J.G. and D.J. Scott. 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.

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

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

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

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.

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

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

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

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

Hodgson, J. and A.W. Illius. 1996. The ecology and management of grazing systems. CAB International, Oxford. pp 466.

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

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

Hsaio, T.C., E. Acevedo, E. Fereres and D.W. Henderson. 1976. Water stress, growth and osmotic adjustment. Philosophical Transactions of the Royal Society London **273:** 479-500.

ISTA. 1993. International rules for seed testing. Seed Science and Technology (supplement) **21:** 1-288.

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

Kanneganti, V.R and S.D. Klausner. 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.

Kemp P.D. and L. Blair. 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.

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.

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.

Larcher,W. 1995. Natural environmental constraints. Pages 321-448 *in* Physiological Plant Ecology. Springer, Berlin.

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

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

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

Mengel, K. and E.A. Kirkby. 1987. Nutrient uptake and assimilation. Pages 113- 191 *in* Principles of plant nutrition. International Potash Institute, Bern.

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 **IV:** 16-25.

Pyke, N. B. 1996. Arable farming - with research into the next century. Proceedings of the Agronomy Society of New Zealand **26:** 9-12.

Rolston, M.P. 1995. Ryegrass 2000: Proceedings of the International Herbage Seed Conference **3:** 296-297.

Rolston, M.P., J.S. Rowarth, J.M. DeFilippi and W.J. Archie. 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.

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

Rowarth, J.S. and W.J. Archie. 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.

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

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

Rowarth, J.S., P.T.P. Clifford, W.J. Archie and B.R. Guy. 1993. Technology transfer and the seed industry: a success story. Proceedings of the Agronomy Society of New Zealand **23:** 113-115.

Rowarth, J.S., Q.F. Jin and W.R. Scott. 1994. Nitrogen recovery efficiency in a browntop seed crop. Soil News **42:** 156.

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.

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.

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

Schöberlein, W and H.J. Wahl. 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 Grasslands Congress **II:** 1695-1696.

Smyth, A.J. and J. Dumanski. 1994. Progress towards an international framework for evaluating sustainable land management (FESLM). Proceedings of the 15th World Congress of Soil Science, Mexico. Vol **6a:** 398-409.

Syers, J.K., A. Hamblin and E. Pushparajah. 1994. Development of indicators and thresholds for the evaluation of sustainable land management. Proceedings of the 15th World Congress of Soil Science, Mexico. Vol **6a:** 398-409.

Welch, R.M. 1986. Effects of nutrient deficiencies on seed production and quality. *in* P.B. Tinker and A. Lauchli eds. Advances in plant nutrition. Vol. 2. Praeger, New York.

White, J.G.H. 1990. Herbage seed production. Pages 370-408 *in* R.H.M. Langer ed. Pastures. Oxford University Press, Auckland.

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

Young, W.C.III., D.O. Chilcote and H.W. Youngberg. 1995. Seed yield responses of perennial ryegrass to spring applied nitrogen at different rates of paclobutrazol. Journal of Applied Seed Production **13:** 10-15.