

More feed for New Zealand dairy systems

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Abstract

An upper limit to productivity of perennial ryegrass–white clover pastures in New Zealand at about 15 t DM/ha per year has been identified as a constraint to future increases in productivity. With potential yields of 26.6 t DM/ha per year from temperate grasses and 45 t DM/ha per year from maize at mid-latitudes, the challenge for New Zealand dairy farming systems is to achieve greater than 15 t DM/ha per year without imposing additional production or environmental costs. Given these constraints a major switch to crops is not feasible because those that produce more than pasture, e.g., maize, have insufficient crude protein to support lactation. Theoretically, a farm area allocation to 78% perennial ryegrass–white clover and 22% maize–winter oats could provide 23.3 t DM/ha per year at a crude protein content of 16%. This is greater than the 20 t DM/ha per year upper limit of irrigated perennial ryegrass–white clover. Incremental yield improvements of grasses and clovers by traditional plant breeding are low (1.5% per year), and difficult to capture. Future plant breeding gains are more likely to come from increased plant stress tolerance. Improved pasture monitoring to allow timely removal of constraints, will enable potential yields to be achieved. Biotechnology offers the possibility of improving the potential yield of net photosynthesis by 20% either through the transfer of genes from a C₄ plant (e.g., maize) or a C₃ plant (e.g., perennial ryegrass), or use of the major photosynthetic enzymes, rubisco, from a thermophilic alga. Biotechnology is also providing new knowledge about the control of plant development and response to stresses. The application of this knowledge may allow dairy farmers to achieve another 5 t DM/ha per year from perennial ryegrass–white clover pastures.

Keywords: biotechnology, dairy, perennial ryegrass, photosynthesis, white clover, yield limitation

Introduction

“Permanent pasture handled with an intensive year-round grazing system never has produced up to the potential that climate allows, and never can” (Mitchell 1966). Mitchell used this statement to introduce a paper that examined the use of alternative forage crops for livestock feeding. The ‘oil shocks’ of the 1970s coupled with low commodity prices ensured that his ideas were never fully tested at a farm scale. Given the increased use of alternative feeds in New Zealand farming systems, particularly dairying, it is timely to re-examine his claim.

The biological maximum for maize yield was calculated to be about 45 t DM/ha per year at 40° latitude (de Wit 1967) based on knowledge of photosynthetic efficiency and respiratory losses. Assuming a 50% harvest index, then the grain yield limit should be 22.5 t DM/ha. This figure has, in fact, been recorded in rain-fed maize in Iowa (Duvick & Cassman 1999). However, in the past decade several authors have identified a ‘yield limitation’ for ryegrass–white clover pastures at about 15 t DM/ha per year that is constraining future increases in animal production from pasture-based feeding systems (Hodgson 1989; Deane 1999). This constraint has been partially overcome by the use of maize silage and food industry by-products (e.g., brewers’ grain, citrus and vegetable residues), but this has inevitably led to increased costs per unit milk produced.

The challenge for New Zealand agriculture is to break this ‘yield limitation’ in such a way that our unit feed costs remain lower than our international competitors. This paper examines the constraints to further productivity and suggests ways to remove them.

Light, water, and soil fertility

Scott *et al.* (1985) showed that approximate estimates of pasture production and its seasonality for different regions of New Zealand can be obtained by considering three important environmental factors: temperature (strongly linked to light), moisture supply, and soil fertility. If the yield limitation is to be broken we

need to understand these environmental limits to pasture productivity.

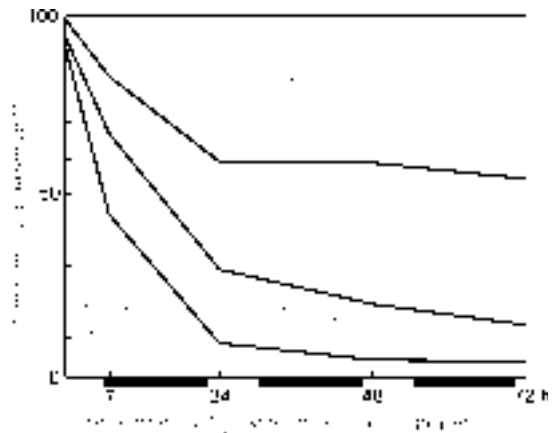
The units of light energy are photons. On a sunny summer day in the Waikato, there are about 840 quintillion (8.4×10^{20}) photons arriving per m^2 per second. In theory, 10 photons are sufficient to trap one molecule of carbon dioxide (Salisbury & Ross 1992), and sixty photons would produce one molecule of glucose. If every photon were used to make glucose at this theoretical efficiency, we would have pasture growth rates of around 1500 kg DM /ha for each hour of sunshine. There are many reasons why this is never achieved. However, the calculation is a provocative starting point to allow us to question whether the yield limitation is a reality, or a limitation we impose on ourselves by not exploiting all possibilities.

Cooper (1970) noted maximum herbage accumulation rates of 26.6 t DM/ha/year, (2.2% conversion efficiency of light energy), for temperate forage grasses recorded at Te Awa by Suckling (1960), and 85.2 t DM/ha/year for Napier grass (*Pennisetum purpureum*) in El Salvador (5.4% conversion of light energy). Even these yields and conversion efficiencies are the exception rather than the rule. Collated data of Hodgson (1989) suggest that around 14 t DM/ha/year is the normal maximum with a little over 20 t DM/ha/year recorded in some recent dairy trials (Penno *et al.* 1996). Such values represent less than 5% available light energy. In practice, even lower conversion of light energy may arise for various reasons, including poor canopy structure, high respiration, lower soil fertility, and water stress (McMurtie 1999).

The major photosynthetic enzyme, rubisco, evolved under carbon dioxide levels four to ten times greater than at present (Eamus 1998). C_3 plants, e.g., perennial ryegrass and white clover, are less efficient at capturing carbon dioxide than C_4 plants, e.g., maize, because of photorespiration which partially reverses the photosynthesis reaction. In addition, plants release carbon dioxide through normal metabolic processes of cell division, cell maintenance, and growth (Figure 1). Robson (1982) studied plants selected for high leaf production but lower respiration loss in mature leaves. The low respiration line maintained a higher tiller population and leaf area index in mini-swards than did the high respiration line. These differences led to a yield advantage in excess of 20%. However, in field swards the yield increase in the low respiration line was less than 10%, for undetermined reasons, and no commercial cultivar was released based on selection for low respiration. Similarly, selection for leaf angle to optimise light capture and photosynthetic utilisation

has produced productivity increases in experimental plant populations, but no new cultivars based on the selected material (Parsons 1994).

Figure 1 Fate of photosynthate as determined from ^{14}C -labelled carbon dioxide to perennial ryegrass plants. R + TM = roots and temporary metabolites. Note 40% respiration losses in the first 24 hours and about 40% retention in permanent tissues. Source: Ryle & Gordon (1978).



New Zealand pastures are subjected to the highest temperatures of the year in late summer, early- autumn, but light levels are decreasing from the summer solstice (Figure 2). Very often these conditions are associated with soil moisture deficit. In such conditions, respiration increases linearly with temperature, and rates of leaf elongation and other growth processes are high, while photosynthesis is reduced by higher-than-optimum temperatures (Watschke *et al.* 1973). As a result, levels of soluble carbohydrate in plant tissue are depleted, plants are stressed and susceptible to overgrazing, and animal performance suffers from both poor nutritive value and low pasture allowance. If light, temperature and moisture are at optimal levels the next limiting factor is likely to be soil nutrients.

Optimum soil nutrient test values for pasture growth have been defined for dairy, beef, and sheep farming on the major soil types (Roberts & Edmeades 1993; Morton *et al.* 1994). Analysis of soil test records showed that 38% of Olsen P test values on dairy farms, and 54% of Olsen P values on sheep-beef farms were below optimum values (Butler & Johnston 1997). Therefore, on a sector-wide basis there is still considerable scope to grow more feed by optimising fertiliser inputs. Nitrogen (N) fertiliser use is increasing steadily, especially in dairying. More milk solids were produced with 400 kg N/ha than with 200 kg N/ha (Ledgard *et*

al. 1997), although most of the increase was gained by applying only 200 kg N, and this was the most profitable option (Penno *et al.* 1996). This suggests that further production increases may be obtained with increased use of N fertiliser.

Crops

A number of annual crops have been grown on-farm to provide extra feed especially during summer. The potential exists for both brassica and C₄ crops, such as maize and sorghum, to grow more DM over summer and autumn than does perennial ryegrass–white clover. However, they have generally failed to provide a solution to the yield limitation problem.

Clark (1995) reported on a nationwide survey of turnip crops showing a mean yield of 7.4 t DM/ha with a maximum yield of 15.2 t DM/ha. Simulation studies showed that crops of 8–10 t DM/ha could provide a break-even return. However, in the survey less than 5% of the farm was used for growing turnips because farmers recognised that larger proportions placed too much grazing pressure on the remainder, both in late spring, when a turnip crop is establishing, and late autumn, when replacement pasture is sown. Even a crop yielding 45 t DM/ha per year, when grown on 5% of the farm with pasture yielding 15 t DM/ha per year, will only contribute 10% more total DM per farm.

Maize shows the most promise as a crop to break the yield limitation. There continues to be a major private sector breeding effort into new maize hybrids coupled with substantial agronomic research and development (Duvick & Cassman 1999). These authors cite grain yields of 22.5 t DM/ha from rain-fed, grain yield contest fields in the US.

However, from a ruminant nutrition perspective, maize grain, or silage is not a complete ration unlike perennial ryegrass–white clover. The major reason is the low crude protein (CP) content of 8–9% compared with a crude protein requirement of 16% for a lactating cow. The yield limitation problem can be stated as what combination of crops or pasture to grow on a unit area of land to maximise DM yield given the constraint that the total yield must contain enough crude protein (16%) to support the cow’s lactation potential. Table 1 shows the assumptions used to arrive at a sustainable area of maize grown for silage on a perennial ryegrass–white clover farm.

Figure 2 Seasonal variation in theoretical sunlight energy on a cloudless day and actual daily maximum temperatures for Ruakura, 1996–1998.

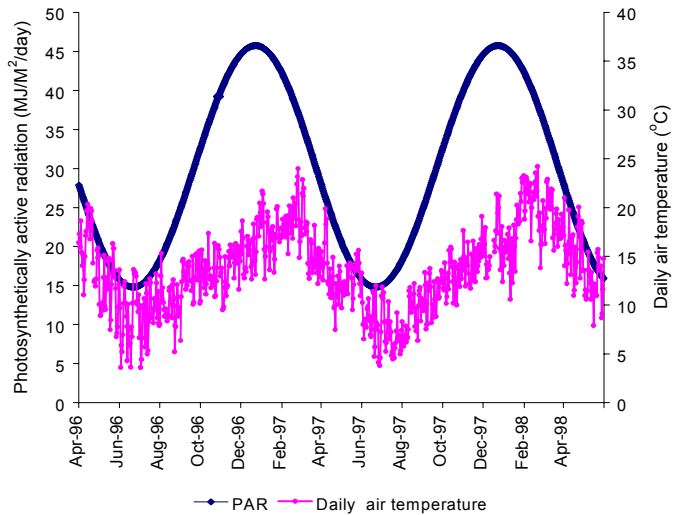


Table 1 Assumptions of yield and crude protein content used for perennial ryegrass, white clover, maize and oats to calculate maximum area of maize to provide a complete ration for lactation cows.

Feed	Yield (t DM/ha/year)	Crude protein (%)
Perennial ryegrass	16	17.5
White clover	4	30
Maize	25	8
Oats	10	8

Maximum DM yield is provided by growing maize (25 t DM/ha) followed by winter oats (10 t DM/ha), both for silage, on 100% of the farm to give 35 t DM/ha per year (Thom & Gillespie 1984). But this option provides a sub-optimal ration of 8% CP. Growing only perennial ryegrass–white clover yields 20 t DM/ha/year (Penno *et al.* 1996) with a crude protein content of 20%. Calculations, not shown here, indicate that the option that maximises DM yield (23.3 t DM/ha) at the optimal CP content of 16% would consist of 78% of the area in perennial ryegrass–white clover and 22% in maize and oats. This represents a 16.5% increase in DM yield compared with 100% of the area sown in perennial ryegrass–white clover. That amount of extra feed would have to provide sufficient milksolids to cover the extra costs of growing and feeding the crop as silage. Currently many farmers break the yield limitation by growing or purchasing such crops off-farm. However, in the long term, growth of the human population will mean that only the most efficient methods of producing animal protein will survive, and

these will be evaluated on their economic and environmental performance per unit area of land, no matter where that land is situated.

Traditional plant breeding

Traditional breeding of grasses and clovers has produced genetic gains of 0.25–1.49%/year (Woodfield 1999), with most gains being less than 1% when animal production was assessed. These results are comparable with progress in other crops. Incorporation of new genetic techniques such as marker-assisted selection will allow more precise breeding for individual traits, without raising the issues surrounding genetically engineered plants. Future prospects are for non-transgenic breeding to become more efficient in delivery of plants that are better adapted to the requirements of pastoral farmers.

Achieving high plant yield is conceptually simple – maximise the extent and duration of radiation interception, use captured energy efficiently in photosynthesis, partition assimilates to give optimal leaf, stem, root, flower structures and maintain these structures at minimum cost (Loomis & Amthor 1999).

There is a perception in New Zealand that maize breeders have made outstanding progress whilst pasture plant breeders have been much less successful (Deane 1999) in increasing the yield potential of their target plants. ‘Yield potential’ is defined as the yield of a cultivar in environments in which it is adapted, with nutrients and water non-limiting and pests, diseases and weeds effectively controlled (Evans & Fischer 1999). However, Duvick & Cassman (1999) found that when maize cultivars developed from 1930–1990 were compared at a low density of 10 000 plants/ha, there were no yield differences. However, at a density of 79 000 plants/ha there was an improvement from 4.5 t grain/ha in 1930 to 12 t grain/ha in 1990. They concluded “although it is clear that genetic improvement has contributed significantly to maize yield advances in farmers’ fields, it is not clear that breeders have been successful in achieving greater yield potential”. They attribute 50% of gains to genetic improvement of stress tolerance and 50% to improvements in agronomic practices.

It appears that selection in a wide range of crop and pasture plants has not changed the efficiency of the photosynthetic process, although C_4 plants are known to be more efficient than C_3 plants in carbon reduction especially at high temperatures and low CO_2 concentration. Therefore, genetic engineering solutions are likely to be needed in order for fundamental improvements in photosynthesis to be made.

The ‘stay-green’ concept has contributed to increased maize yields and may have a place in ryegrass breeding. This concept is based on delayed senescence of mature leaves so that extra photosynthate is available for grain filling. To be successful it relies on adequate N supply, but in ryegrass, delayed senescence would not only increase green leaf allowance but, in summer, it would reduce the amount of litter as a growth medium for the fungus *Pithomyces chartarum*, the spores of which cause facial eczema.

Increased maize grain yields have been associated with a 2% unit decrease in grain protein and a 2% unit increase in grain starch from 1960–2000 (Duvick & Cassman 1999). Protein is energetically more expensive to produce (0.4 g protein/g glucose) than starch (0.83 g starch/g glucose) respectively (Loomis & Amthor 1999). Given that both ryegrass and white clover have protein contents in excess of ruminant requirements there is potential for ryegrass breeders to reduce protein and increase carbohydrate content. This may lead to both higher total yield and improved nutritive value although high water soluble carbohydrate lines may suffer from greater insect predation.

Traditional breeding must continue to provide stress tolerant ryegrass and white clover plants if the yield potential of these plants is to be realised. The incorporation of the AR1 endophyte into recent perennial ryegrass cultivars is an excellent example of plant protection coupled with direct advantages for animal welfare (Fletcher 1999).

Biotechnology

Genetic engineering may offer the best opportunity to increase the photosynthetic efficiency of C_3 plants such as perennial ryegrass and white clover. One option could be to transfer genes from a C_4 plant such as maize. Ku *et al.* (1999) report some success in transferring genes associated with photosynthesis control from maize to rice. They envisage an increase of 20% in the yield potential through this mechanism. Another option is to use rubisco from the thermophilic algae (*Galderia partita*) to increase CO_2 binding to the enzyme. Uemara *et al.* (1997) predict a 20% increase in potential yield from the process.

There is scope in both ryegrass and white clover to reduce protein and increase carbohydrate contents by molecular approaches. This would release energy for increased yield, improve nutritive value and reduce N losses to the environment. The latter two objectives would also be achieved by having condensed tannins expressed in white clover leaf and petiole tissue. Currently, AgResearch are developing high-energy ryegrasses aimed at improving animal performance.

There are exciting possibilities for increasing yield potential through genetic engineering. Molecular biological techniques are providing new knowledge about control of plant development and response to stresses. This knowledge can be exploited to produce plants with novel traits not achievable by conventional breeding. Higher herbage yields are likely to be achieved first, by incorporating genes controlling mechanisms for resistance to root pruning insect pests. However, if assisted cross-species gene transfer is involved, there may be regulatory and market place opposition to the plants entering the food chain. The economic importance of anti-GE attitudes is uncertain.

Management of constraints

The grazing process is a major reason why permanent pasture does not produce up to the potential that climate allows. The periodic removal of immature leaves imposes a constraint on the yield attained; the interaction between grazing removal and carbon capture by photosynthesis is now well understood (Johnson & Parsons 1985). The potential solutions of removing the grazing animal and/or changing the plant species have not been adopted in New Zealand because of the low product price: input cost ratios for our major products.

If we are to continue using perennial ryegrass-white clover pastures as the basis for our animal production then the potential of new cultivars will only be achieved by removing several severe constraints. Excess or deficient water supply restricts the growth of New Zealand pasture even in the most intensive enterprises. The continuing expansion of dairying into irrigated areas of the South Island, reflects, in part, the acceptance that dairying in future will not tolerate 200-day lactations dictated by poor pasture growth during droughts. In areas without irrigation, greater emphasis must be placed on maintaining pasture density and a healthy root environment. Both criteria require avoidance of soil compaction and the provision of optimal plant nutrition.

For Waikato and Bay of Plenty dairy farms supplied by BOP Fertiliser, average fertiliser N inputs on farms that used N increased from 62 kg N/ha in 1995/96 to 81 kg N/ha in 1999/2000 (T.J. Johnston pers. comm.). Despite this, the visual evidence of N deficiency in pastures remains at most times of the year. Disappearance of white clover from many dairy farms in northern New Zealand in the late 1990s as a consequence of clover root weevil (*Sitona lepidus*) attack is likely to compound N deficiency. However, 300 kg N/ha is applied to maize crops, with additional N fertiliser if a winter crop is grown. Yield potential

of new ryegrass cultivars will not be reached without increased levels of N, either from fertiliser or from legume fixation. A balance between economic and environmental factors will set the limit to this approach.

Even if the above constraints are removed there will still be a requirement for control of insect pests such as black beetle, Argentine stem weevil and clover root weevil and nematodes, weeds and diseases.

Conclusions

Traditional ryegrass and white clover plant breeders are likely to continue to make genetic improvements of up to 1% per annum in DM yield. This will be through increasing stress tolerance. For farmers to access these improvements they will need to increase the monitoring of pastures and act quickly to alleviate stressors. These advances are available in the short-term and on all farms.

Unless crops can be grown, harvested and fed for much lower costs than is currently possible, or product prices rise significantly, it is unlikely that self-contained farms will grow more than 25% of their area in such crops.

In the long term, biotechnology offers the prospect of increasing pasture yields by 20% from 20 t DM/ha per year currently to 25 t DM/ha per year as a result of fundamental changes in photosynthetic mechanisms. Improvements in agronomic practices will ensure that potential yield is achieved more often than in the past.

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REFERENCES

- Butler, P.J.; Johnston, T.J. 1997. Fertiliser use in the Bay of Plenty, Waikato and South Auckland regions. *Proceedings of the New Zealand Grassland Association* 59: 35–37.
- Clark, D.A. 1995. Summer milk – pasture and crops. *Proceedings of the Ruakura Farmers' Conference* 47: 10–16.
- Cooper, J.P. 1970. Potential production and energy conversion in temperate and tropical grasses. *Herbage Abstracts* 40: 1–15.
- Deane, T. 1999. The profitable use of supplementary feeds in pasture based dairy farm systems. *Proceedings of the Ruakura Farmers' Conference* 51: 64–77.

- de Wit, C.T. 1967. Photosynthesis: its relationship to overpopulation. pp. 315–320. *In: Harvesting the sun*. Ed. Son Pietro, A. *et al.* Academic Press, New York.
- Duvick, D.N.; Cassman, K.G. 1999. Post-Green revolution trends in yield potential of temperate maize in the North-Central United States. *Crop Science* 39: 1622–1630.
- Eamus, D. 1999. C₄ Subgroups. pp. 60–64. *In: Plants in action*. Eds. B.J. Atwell *et al.* Macmillan, South Yarra, Australia 3141.
- Evans, L.T.; Fischer, R.A. 1999. Yield potential: its definition, measurement and significance. *Crop Science* 39: 1544–1551.
- Fletcher, L.R. 1999. “Non-toxic” endophytes in ryegrass and their effect on livestock health and production. pp. 133–139. *In: Ryegrass endophyte: an essential New Zealand symbiosis*. Eds. Woodfield, D.R.; Matthew, C. *Grassland Research and Practice Series No. 7*.
- Hodgson, J. 1989. Increases in milk production per cow and per hectare: pasture production. *Dairy Farming Annual* 41: 76–82.
- Johnson, I.R.; Parsons, A.J. 1985. A theoretical analysis of grass growth under grazing. *Journal of Theoretical Biology* 112: 345–367.
- Ku, M.S.B.; Agarie, S.; Nomura, M.; Fukuyama, H.; Tsuchida, H.; Ono, K.; Hirose, S.; Toki, S.; Miyao-Tokutum, M.; Matsuoka, M. 1999. High level expression of maize phosphoenolpyruvate carboxylase in transgenic rice plants. *Nature Biotechnology* 17: 72–80.
- Ledgard, S.F.; Penno, J.W.; Sprosen, M.S. 1997. Nitrogen balances and losses on intensive dairy farms. *Proceedings of the New Zealand Grassland Association* 59: 49–53.
- Loomis, R.S.; Amthor, J.S. 1999. Yield potential, assimilatory capacity and metabolic efficiencies. *Crop Science* 39: 1584–1596.
- McMurtie, R.E. 1999. Pine forest canopies and biomass production. pp. 406–409. *In: Plants in action*. Eds. Atwell, B.J. *et al.* Macmillan, South Yarra, Australia 3141.
- Mitchell, K.J. 1966. Alternative forage crops for livestock feeding. *New Zealand Agricultural Science* 1: 23–29.
- Morton, J.; Roberts, A.H.C.; Edmeades, D.C. 1994. Fertiliser use on beef and sheep farms. New Zealand Fertiliser Manufacturers Research Association, 38 pp.
- Parsons, A.J. 1994. Exploiting Resource Capture – Grassland. pp. 315–349. *In: Resource Capture by Crops*. Eds. Monteith, J.L.; Scott, R.K.; Unsworth, M.H. Nottingham University Press, Loughborough, UK.
- Penno, J.W.; Macdonald, K.A.; Bryant, A.M. 1996. The economics of No 2 dairy systems. *Proceedings of the Ruakura Farmers’ Conference* 48: 11–19.
- Roberts, A.H.C.; Edmeades, D.C. 1993. Fertiliser use on dairy farms. Dairy Research Corporation, 37 pp.
- Robson, M.J. 1982. The growth and carbon economy of selection lines of *Lolium perenne* cv. S23 with differing rates of dark respiration 1. Grown as simulated swards during a regrowth period. *Annals of Botany* 49: 321–329.
- Ryle, G.J.A.; Gordon, A.J. 1978. The biochemistry of carbon utilisation during the growth of Graminaeous plants. Pp. 68–70 *In: Annual report 1977*. Grassland Research Institute, Hurley, Maidenhead, Berks, UK.
- Salisbury, F.B.; Ross, C.W. 1992. Plant physiology (4th Edn.) Wadsworth, Belmont, California. 682 pp.
- Scott, D.; Keoghane, J.M.; Cossens, G.G.; Maunsell, L.A.; Floate, M.J.S.; Wills, B.J.; Douglas, G. 1985. Limitations to pasture production and choice of species. pp 9–15. *In: Using Herbage Cultivars*. Eds. Burgess, R.E.; Brock, J.L. *Grassland Research and Practice Series No. 3*.
- Suckling, F.E.T. 1960. Productivity of pasture species on hill country. *New Zealand Journal of Agricultural Research* 3: 579–591.
- Thom, E.R.; Gillespie, R.N. 1984. The contribution of forage oats to annual feed production when grown after maize in a double cropping system. *New Zealand Journal of Experimental Agriculture* 15: 419–423.
- Uemara, K.; Anwaruzzaman, S.; Miyachi, S.; Yokota, A. 1997. Ribulose -1, 5- biphosphate carboxylase/ oxygenase from thermophilic red algae with a strong specificity for CO₂ fixation. *Biochemical, Biophysical Research Communication* 233: 568–571.
- Watschke, T.L.; Schmidt, R.E.; Carson, E.W.; Blaser, R.E. 1973. Temperate influence on the physiology of selected cool season turfgrasses and bermudagrass. *Agronomy Journal* 65: 591–594.
- Woodfield, D.R. 1999. Genetic improvements in New Zealand forage cultivars. *Proceedings of the New Zealand Grassland Association* 61: 3–7.