Trajectory and causes of decline in the botanical composition of dairy-grazed pasture in the Waikato

J.M. LEE[1], E.R. THOM[1], C.D. WAUGH[1], N.L. BELL[2], M.R. McNEILL[3], D.J. WILSON[2] and D.F. CHAPMAN[4]
[1]*DairyNZ, Private Bag 3221, Hamilton 3240, New Zealand*
[2]*AgResearch Ltd, Ruakura Research Centre, Private Bag 3123, Hamilton 3240, New Zealand*
[3]*AgResearch, Lincoln, Private Bag 4749, Christchurch 8140, New Zealand*
[4] *DairyNZ, P.O. Box 160, Lincoln University, Lincoln 7647, New Zealand*
david.chapman@dairynz.co.nz

Abstract
Herbage accumulation, botanical composition, tiller density and insect pest populations were monitored over 6 years for four perennial ryegrass functional types grazed by dairy cows in the Waikato. The aim was to identify genotypic and environmental factors contributing to ryegrass persistence failure in the upper North Island. Perennial ryegrass content of pastures declined as low as 60% of total herbage mass (HM) in summer of the first 3 years but recovered in autumn to at least 75%. However, following two successive severe summer/autumn droughts in Years 2 and 3, and subsequent grass grub larvae populations exceeding the damage threshold of 200/m^2, by 4 years after sowing (autumn 2015), ryegrass had fallen to 20% of HM. This pattern was repeated in the following 2 years, and was not prevented by any combination of ryegrass functional type, endophyte, seeding rate, or best-practice dairy cattle grazing and soil nutrient management. The abiotic and biotic environmental stresses dominated all other factors.

Keywords: pasture persistence, perennial ryegrass, drought, insects, black beetle, dairy systems

Introduction
Dairy farmers in the upper North Island of New Zealand frequently report poor persistence of recently sown perennial ryegrass pastures (Reynolds 2013; Scott 2013). Surveys of the perspectives of dairy farmers in the Waikato and Bay of Plenty regions regarding pasture renewal (Kelly *et al.* 2011; Rijswijk & Brazendale 2016) reveal they have little confidence that the performance of new pastures will be sustained beyond 2 years post-sowing. Using survey data reported by Kelly *et al.* (2011) for the percentage of farm area renewed annually on dairy farms in the Bay of Plenty, the average renewal rate when the survey was conducted (early 2011) was just over 20% of farm area. Thus, on average, the entire farm area is being sown to new pasture every 5 years.

This is not necessarily a new problem. Thom *et al.* (1998) observed a decline in perennial ryegrass content and dry matter (DM) yield of ryegrass pastures over 3 years (from 1992/1993 to 1994/1995) in a cultivar comparison at Ruakura in the Waikato, such that ryegrass frequency (assessed using the point quadrat method) averaged 37% (range 23-46%) in winter 3 years after sowing. Thom *et al.* (1998) questioned the ability of the cultivar entries used in the trial (all of which had high levels of endophyte infection with the standard endophyte, SE, except for an uncertified line of 'Grasslands Nui') to persist under the climatic conditions at this site when grazed by dairy cattle. The cultivar entry list included several cultivars derived from the Mangere ecotype collected from dairy pastures in south Auckland in the 1960s (Armstrong 1977). This ecotype remains a key source of germplasm for current perennial ryegrass breeding programmes in New Zealand (Stewart 2006).

Many factors are likely to be driving the recent trend toward frequent pasture renewal including: drier, hotter summer and autumn conditions, likely interacting with variation among soil types in water holding capacity; and more-frequent occurrences of damaging insect pest population densities, especially black beetle (*Heteronycus arator* (Fabricius)), also likely interacting with soil type (Clark 2011; Gerard *et al.* 2013). Management factors such as increased stocking rate (from 2.1 to 2.8 cows/ha, on average, from 1979 to 2009) and over-grazing of pastures, particularly during summer, have also been implicated (Macdonald *et al.* 2011). Disentangling the relative effects of these factors (environmental, including insect pests; genetic, including the grass and the associated endophyte; and management) is hampered by the absence of data from long-term (i.e. >3 years) experiments that relates changes in the yield, composition and population density of different ryegrass functional types to key environmental factors.

From a practical perspective, it is the persistence of the yield advantage gained by sowing a new pasture that matters for farmers (Parsons *et al.* 2011), and this high-level definition of 'persistence' is used here. This expected yield advantage can only 'persist' if the sown species continues to contribute a high proportion of

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the total herbage mass, which in turn requires physical survival of the plant population. In grass-based pastures, these two variables are typically assessed by measuring pasture botanical composition and tiller density. This paper relates trends in both variables to environmental factors using data from an experiment comparing four perennial ryegrass cultivars (representing different functional types) under dairy cattle grazing for 6 years after sowing in the Waikato. The core objective was to separate genotype and environment effects, albeit using a limited range of plant cultivars sown with endophyte strains conferring protection against major insect pests that cause pasture damage in the upper North Island (Popay & Hume 2011).

Materials and methods

The experiment was conducted at DairyNZ's Scott Farm at Newstead, Waikato (-37.772, 175.378; 40 m a.s.l.) on a Matangi silt loam. Full experimental details are provided by Lee *et al.* (2016). Briefly, four perennial ryegrass cultivars ('Grasslands Nui' SE, 'Grasslands Commando' AR37, Alto AR37, Halo AR37) were selected for the experiment that represented different functional types, i.e. 'old' Mangere-type mid-season heading diploid, modern mid-season diploid, late-season diploid, and late-season tetraploid, respectively. Pre-sowing tests for endophyte viability confirmed endophyte infection frequencies of 87, 74, 84 and 78% of seed for Nui, Commando, Alto and Halo, respectively. Each cultivar was sown with white clover in plots at five seeding rates (equivalent to 6, 12, 18, 24 and 30 kg seed/ha). Main treatment plots (cultivar, 540 m^2) were divided into sub-plots (seeding rate, 108 m^2), arranged in a randomised split-plot design with five replicates. Ultrastrike®-treated ryegrass seed was direct-drilled on 29th March 2011. On 30th March, Superstrike®-coated white clover seed (equivalent to 5 kg/ha of bare seed: cultivar 'Grasslands Tribute') was oversown. Further details of site preparation and management are reported by Lee *et al.* (2016).

All seeding rate treatment sub-plots were monitored for 4 years after sowing. For the next 2 years, only the 18 kg/ha treatment sub-plots were sampled as the effects of seeding rate had dissipated (Lee *et al.* 2018). This paper reports the continuous dataset from the 18 kg/ha treatment only.

Management

All plots were rotationally grazed by dairy cows when the herbage mass (HM) was between 2500 and 3500 kg DM/ha (minimum 2-leaf stage), to a target post-grazing residual of 1600 kg DM/ha (approximately 5 cm residual stubble height). Between nine and ten grazing events occurred/year. During the peak of seedhead production, when clumps of herbage were left ungrazed around dung pats and urine-affected areas, plots were mown to a stubble height of ~7 cm after grazing. This occurred between one and six times/year. Maintenance fertiliser was applied pre-sowing and annually after soil tests to maintain nutrient levels in the optimum range (Lee *et al.* 2018). Urea was applied four times/year, totalling on average 145 kg N/ha/year.

Climate

Daily weather records were obtained from the Ruakura Meteorological Station (5 km from the site). Data from the first 5 years were used in the DairyMod simulation model (Johnson *et al.* 2008) to look at predicted soil water availability for perennial ryegrass growth (expressed as growth limiting factor, GLF, where 1 = no limitation to growth and 0 = complete limitation).

Herbage accumulation

From the second grazing (June 2011) onwards, HM was estimated by quadrat cuts on the day before grazing. Herbage was cut to the approximate post-grazing height (40 mm) within two square quadrats (0.2 m^2) placed randomly within each sub-plot in three replicates. From December 2012 onwards, one 5 m x 1.5 m strip was cut from alternating sides of each sub-plot in all five replicates using a Haldrup F-55 forage harvester (Haldrup GmbH, Ilshofen, Germany) set to a cutting height of 55 mm (until September 2015) or 45 mm (after September 2015) above ground level. Seasonal herbage accumulation (HA) for each sub-plot was calculated from the HA rate data for individual harvests partitioned within the following periods: winter, 1 June to 31 August; spring, 1 September to 30 November; summer, 1 December to 28/29 February; and autumn, 1 March to 31 May. Total annual HA was also calculated for the period 1 June to 31 May.

Perennial ryegrass tiller density

Perennial ryegrass tiller population densities were calculated from the total number of ryegrass tillers counted in five randomly placed frames (5 x 20 cm) per sub-plot in May, August and November 2011, and every autumn (April/May) thereafter.

Endophyte infection

Fifty perennial ryegrass tillers per sub-plot were randomly cut at ground level from three of the five replicates annually in autumn. The sap from the cut base of each tiller was squeezed onto nitrocellulose blotting paper before colour development that confirmed the presence/absence of endophyte (Hahn *et al.* 2003).

Botanical composition

Representative samples of herbage from each sub-plot

were collected the day before grazing in winter, spring, summer and autumn (August, November, January and April, respectively) each year. Until June 2012, hand-shears were used to cut six 0.5 m strips/ sub-plot in three replicates to the approximate post-grazing height (40 mm). After June 2012, samples of herbage were collected from harvester yield cuts. Samples were blended and a sub-sample dissected into perennial ryegrass, white clover, unsown species and dead material. Dissected sub-samples were oven-dried at 95°C for ~48 hours and weighed to determine botanical composition as a proportion of HM above the residual grazing height.

Invertebrate pest populations

In March 2011, invertebrate populations were assessed before sowing. Twenty spade squares (200 x 200 x 200 mm deep) were removed from the experimental site and all soil macro-invertebrates identified and counted. Following establishment of the plots, invertebrate populations in the 6 and 30 kg/ha sub-plots of all cultivars were assessed annually. The intended timing of sampling was autumn each year; however, occasionally this was delayed until early winter due to drought/low summer rainfall conditions. For samplings between 2012 and 2015, ten soil cores (100 mm diameter x 140 mm depth) were collected from each of the specified sub-plots, and the soil macro-invertebrates were identified and counted. In 2016 and 2017, sampling was changed to two 200 x 200 mm spade squares to at least 140 mm depth per sub-plot which gave the same surface sampling area. There was similar variability in invertebrate populations observed for the two sampling methods.

Statistical analysis

Herbage data were analysed using REML in GenStat 14.1 (VSN International Ltd. 2011) with cultivar (main plot), seeding rate (sub-plot), site and their interactions as fixed effects, and block, main plot within block and sub-plot within main plot as random effects. For botanical composition data, both untransformed and angular transformed were analysed; similar conclusions were drawn from both analyses, therefore, untransformed data are presented here. Fisher's protected least significant difference test was used to identify significant differences between treatment means. Invertebrate data were analysed untransformed by ANOVA in GenStat.

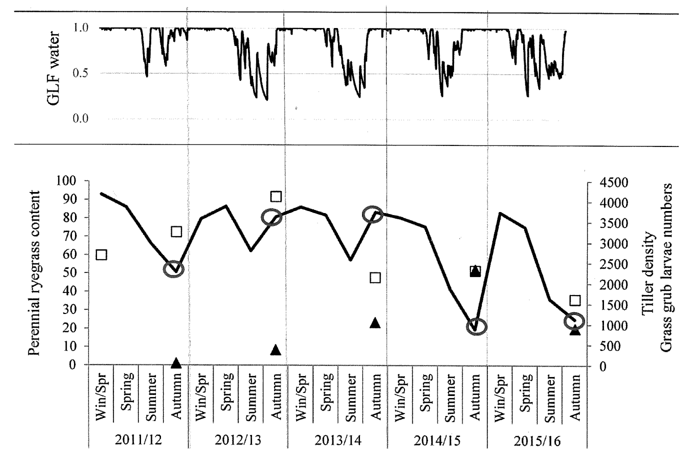

Figure 1 General trends in predicted soil water availability for perennial ryegrass growth (upper panel: modelled in DairyMod using daily climate data from Ruakura, and expressed as growth limiting factor, GLF, where 1 = no limitation to growth and 0 = complete limitation), perennial ryegrass content of pasture (lower panel: % of total pre-graze herbage mass; solid line), perennial ryegrass tiller density (lower panel: no./m^2; squares) and grass grub larvae populations (lower panel: no./m^2 x 10; triangles) over the first 5 years post-sowing of perennial ryegrass pastures in Waikato. Data in the lower panel are means of four perennial ryegrass cultivars. Circled points on the solid line for perennial ryegrass content correspond to autumn measurements.

Results

Climate

Long periods of low summer/early autumn rainfall were experienced in two of the 6 years: in Year 2 from January to March 2013 (3-month total rainfall of 50 mm; 23% of the long-term mean) and in Year 3 from January to March 2014 (3-month total rainfall of 59 mm; 27% of the long-term mean). In Years 4, 5 and 6 total monthly rainfall was also below average for 2-4 months during summer/early autumn. Periods of low rainfall were often combined with warmer than average (by 1-4°C) monthly maximum temperatures. Total Penman potential evapotranspiration generally exceeded rainfall from October to March each year, resulting in accumulated water deficits of -446, -428, -269, -310 and 0 mm for years 2-6. DairyMod revealed that the plant available water content of the soil profile was 50% or less of the content required for unrestricted growth (i.e. GLF <0.5) for 4, 59, 62, 28 and 36 days/ year for the first 5 years (Figure 1), versus 20 days/year for the 10 years preceding the experiment.

Botanical composition

The contribution of perennial ryegrass to total DM yield in summer of the first 3 years dipped as low as 60% (with the exception of Nui in Year 2 which fell to 45%; Figure 2a), but generally recovered in autumn to at least 75% total DM (Figure 1). In the fourth and fifth summers

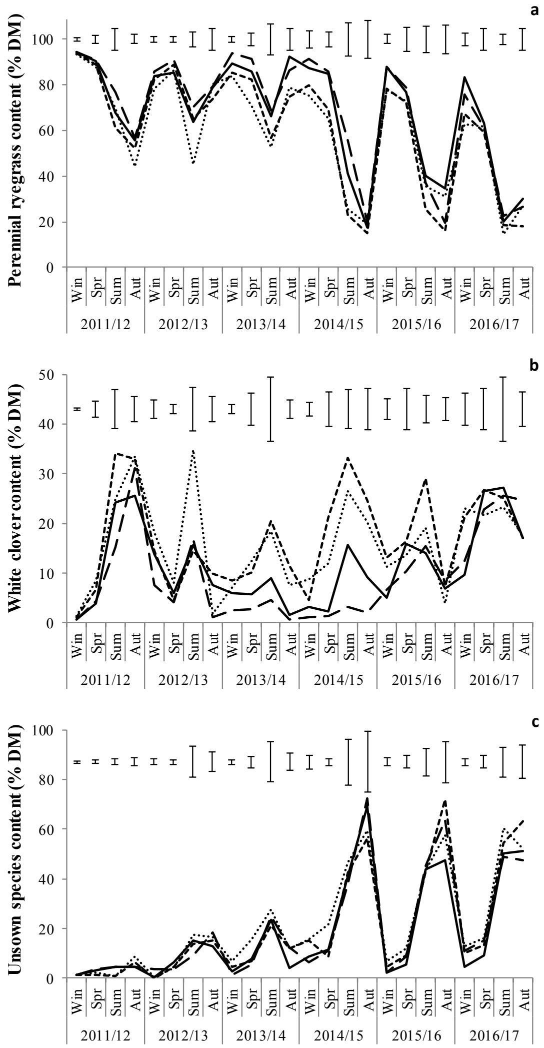

Figure 2 Seasonal content (% DM) of (a) perennial ryegrass, (b) white clover and (c) unsown species in herbage above 40 mm in mixed swards sown with four perennial ryegrass cultivars, Alto (solid line), Commando (short dash line), Halo (long dash line) and Nui (dotted line). Error bars indicate the standard error of the difference between cultivar means. Win, winter; Spr, spring, Sum, summer, Aut, autumn.

(2014/2015 and 2015/2016), it fell to 35%, then fell further in autumn to 18-25%. By the sixth summer, the contribution of ryegrass had further declined to 19%. Meanwhile, the content of summer-active grasses (e.g. paspalum) and broad-leaved weeds (e.g. hawksbeard, dandelion) increased commensurately (Figure 2c).

Pastures sown with Nui had lower ($P<0.05$) perennial ryegrass content than those sown with Halo or Alto in 7 of the 24 seasons for which data were collected (Figure 2a). White clover content was lower ($P<0.05$) in pastures sown with Halo compared with Commando or Nui in 4 of the 24 seasons (Figure 2b), while pastures sown with Nui had greater ($P<0.05$) content of unsown species than those sown with Alto and Halo during 3 seasons (Figure 2c).

Herbage accumulation

Seasonal and total annual pasture HA were similar across cultivars during all seasons and years ($P>0.05$), averaging 17.5, 9.8, 6.8, 7.5, 10.7 and 8.9 t DM/ha/year from Years 1 to 6. Note that while it is valid to compare cultivars within each year, it is not valid to compare HA across years as the height to which herbage was harvested changed in both 2012/2013 (Year 2) and 2015/2016 (Year 5).

The HA of the perennial ryegrass component of pastures was also similar for all cultivars during all seasons and years ($P>0.05$). White clover HA was greater from pastures sown with Commando than Alto or Halo during autumn 2014 ($P<0.05$; +115-120 kg DM/ha), summer 2014/2015 ($P<0.05$; +765-785 kg DM/ha) and during the 2014/2015 year ($P<0.05$; +1415-1840 kg DM/ha). Pastures sown with Commando had greater HA of unsown species than the other three cultivars during winter 2014 ($P<0.05$; +100 kg DM/ha), while pastures sown with Nui had greater HA of unsown species than the other three cultivars during spring 2014 ($P<0.05$; +295 kg DM/ha).

Tiller density

Pastures sown with Nui had a lower density of perennial ryegrass tillers than those sown with the other three cultivars during the first winter ($P<0.001$; 4120 versus 5512, 5672 and 6256 tillers/m^2 for Nui versus Alto, Halo and Commando; SED=355). By late spring 2011, pastures sown with Nui still tended to have lower tiller density than those sown with Commando and Halo ($P=0.085$; 3387 versus 3913 and 4547 tillers/m^2, respectively; SED=388). By the end of the first year after sowing (autumn 2012), pastures sown with Halo tended to have a lower tiller density than those sown with Commando ($P=0.094$; 2727 versus 5520 tillers/m^2, SED=939), a trend that continued to the end of the second year after sowing ($P=0.062$; 3453 versus 6407 tillers/m^2; SED=950). No cultivar effects on tiller density were recorded beyond this point ($P>0.05$).

Endophyte infection

Endophyte infection of all cultivars remained above 80% throughout the 6 years, with the exception of Commando in autumn 2012 (74%).

Invertebrate pest populations

Before sowing, soil macro-invertebrate populations were low, with eight black beetle (adult + larvae)/

m^2, two clover root weevil (*Sitona lepidus*) larvae/m^2 and two white-fringed weevil (*Naupactus leucoloma*) larvae/m^2. No New Zealand grass grub (*Costelytra zealandica*) were found. No significant differences in grass grub abundance were recorded between cultivars during the 6 years ($P>0.05$). Grass grub populations increased after sowing (5, 38, and 105/m^2 in March 2012, June 2013 and June 2014, respectively; Figure 1), reaching significantly damaging levels of 234/m^2 in May 2015 (end of Year 4), after which they declined to 90 and 128/m^2 in the subsequent 2 years. For the combined 6 years of data there was a significant effect of cultivar on black beetle populations with more beneath Commando than Halo (7.0 versus 2.7/m^2) with Nui and Alto intermediate (both 4.8/m^2; LSD = 2.9; $P<0.05$). The largest differences in black beetle abundance beneath Commando and Halo were observed in the 2014 (15.2 versus 3.8/m^2) and 2015 (8.9 versus 0/m^2) samplings (LSD=7.1 for cultivar × year interaction). The black beetle population, on average, remained below 10/m^2 for the 6 years with small peaks in 2014 and 2015 when 10% of the sub-plots had damaging levels of >20/m^2. Other insect pests of ryegrass identified included white-fringed weevil, root aphids and pasture mealey bug, but populations were not at individually damaging levels at any sampling.

Discussion

Seasonal patterns of soil moisture deficit (expressed as the predicted extent to which ryegrass growth was limited by soil moisture deficit), ryegrass percentage of total herbage mass, ryegrass tiller density and grass grub larvae population numbers for the first 5 years of the study are summarised in Figure 1. Two successive, severe summer droughts occurred in Years 2 and 3 after sowing, 2012/2013 and 2013/2014, respectively. The ryegrass content of pastures recovered from drought in autumn 2013 and autumn 2014, but failed to recover in autumn 2015, 4 years after sowing. Ryegrass content did recover in winter and spring 2015, but fell to low levels again in summer 2015/2016 and remained at a low level in autumn 2016. This pattern repeated in 2016/2017, with ryegrass contribution to HM during summer declining further to 19% (Figure 2a). In the 2015/2016 and 2016/2017 years, ryegrass contribution to HM was confined to winter and spring, effectively mirroring the seasonal growth curve of annual ryegrass. This pattern of declining ryegrass content aligns with feedback from farmers in the pasture renewal surveys, that they have little confidence in the performance of their new pastures beyond 2 years post-sowing. Thus, the trends shown in Figures 1 and 2 can be taken as representative of the trajectory of change in ryegrass productivity for situations in the upper North Island as reflected in farmer responses to surveys (Kelly *et al.* 2011; Rijswijk & Brazendale 2016).

The breaking-point for pasture resilience appeared to occur during the summer and autumn of 2014/2015 when dry summer conditions were experienced for the third successive year, with the grass grub larval population also reaching a mean density of 234/m^2 in autumn 2015. Despite good autumn rains in 2015 and the release of moisture stress, perennial ryegrass did not recover: indeed it fell to the lowest values recorded during the study, at around 20% of total HM. Circumstantially, the twin environmental stresses of severe summer soil moisture deficit and grass grub damage to root systems, combined with a ryegrass tiller population that had been depleted 12 months earlier (Figure 1), led to ryegrass being over-run by weed species (Figure 2c; especially paspalum, hawksbeard and dandelion). Pasture state then switched to weed dominance, which continued in the following 2 years. As noted above, taking the seasonal pattern of perennial ryegrass contribution to total pasture DM and tiller density, the pasture essentially switched from a perennial pasture to a winter annual pasture with minimal ryegrass growth in summer and autumn.

Importantly, the outcomes were the same irrespective of whether pastures were sown with old or new ryegrass cultivars, diploids or tetraploids, SE or AR37 endophyte, and low or high seeding rates (Lee *et al.* 2018). Furthermore, implementation of best ryegrass management practices such as maintenance of adequate soil nutrients and consistent grazing to recommended pre- and post-grazing herbage mass targets did not prevent the decline in the ryegrass content of pastures. Hence, environmental conditions dominated all other factors. This conclusion is supported by the observation that ryegrass dominance was sustained over the same time period when the same treatments were sown in Canterbury and subject to the same management protocols with the addition of irrigation in summer and autumn (Lee *et al.* 2018). Thus, we conclude that perennial ryegrass technology as at 2011 and management to prevent the collapse of ryegrass content in the face of combined, severe environmental stresses is not currently available.

Dry summers are common in the Waikato, and throughout much of the upper North Island (NIWA 2017). Farmers use a range of tactical management responses to cope with reduced feed supply from pasture in summer, such as early culling, use of supplements such as pasture silage, maize silage or palm kernel expeller, or once-a-day milking. Autumn rains generally release the summer growth limitation (as seen in 2012/2013 and 2013/2014 in this study, Figures 1 and 2), allowing farmers to re-build pasture cover to support late-lactation milk production, body condition score gain and attainment of winter pasture cover targets. Autumn growth is, therefore, important for whole lactation performance, as reflected by the relatively high economic values for additional pasture grown at this time of year (Chapman *et al.* 2012). Failure of autumn pasture recovery is potentially costly as additional feed must be supplied, or cows dried off early reducing total milk production.

Currently, there are no tools available to provide farmers with an early warning of pasture decline so that they could avert, or at least reduce, those costs. In this study, the sharp decline (mean 50% reduction) in ryegrass tiller density between autumn 2013 and autumn 2014 (Figure 1) was, in retrospect, a possible indicator that the ryegrass populations were under pressure. As best as can be determined, soil water deficit was the only major growth stress affecting pasture plants up to this point. Grass grub larvae numbers increased between 2012/2013 and 2013/2014 (Figure 1) but were still well below the damage threshold of 200/m^2 in autumn 2014. No other insect pests present at the site individually posed a threat to pasture growth, but the combined suite of pests would have had an additional cumulative effect on ryegrass resilience (N. Bell, unpublished data). Grazing interval was extended in mid-summer and autumn during dry periods to allow ryegrass to reach the 2-leaf stage (at a minimum) and, when it occurred, the grazing was quick and light to prevent over-grazing. These responses are consistent with recommended grazing practices for maintenance of ryegrass pasture survival during dry summers. The presence of other growth stressors, such as sub-clinical levels of root or foliar diseases or viruses cannot be ruled out. More information, for example, on critical tiller population thresholds below which ryegrass cannot recover to a dominant position in the pasture after the typical summer decline, is needed to help develop simple practical measures that farmers could use to gauge the resilience of their pastures to environmental stresses.

Conclusions

In some areas of the upper North Island, perennial ryegrass may only be a 3- to 4-year dairy pasture option, even where best ryegrass/endophyte genetics and management are used. Farmers that choose to renew perennial ryegrass pastures should continue to use recommended cultivar/endophyte combinations from the Forage Value Index (www.dairynz.co.nz). Alternative solutions are, however, clearly also required. Many farmers have adopted these already, albeit after much trial-and-error. Research and development needs to catch up with farmer experience to help guide profitable, environmentally sustainable responses to the problem of poor perennial ryegrass persistence.

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REFERENCES

Armstrong, C.S. 1977. 'Grasslands Nui' perennial ryegrass (*Lolium perenne* L.). *New Zealand Journal of Experimental Agriculture 5*: 381-384.

Chapman, D.F.; Bryant, J.R.; McMillan, W.H.; Khaembah, E.A. 2012. Economic values for evaluating pasture plant traits. *Proceedings of the New Zealand Grassland Association 74*: 209-215.

Clark, D.A. 2011. Changes in pastoral farming practices and pasture persistence - a review. *Pasture Persistence Symposium. Grassland Research and Practice Series 15*: 7-13.

Gerard, P.J.; Bell, N.L.; Eden, T.M.; King, W.M.; Mapp, N.R.; Pirie, M.R.; Rennie, G.M. 2013. Influence of pasture renewal, soil factors and climate on black beetle abundance in Waikato and Bay of Plenty. *Proceedings of the New Zealand Grassland Association 75*: 235-240.

Hahn, H.; Huth, W.; Schöberlein, W.; Diepenbrock, W. 2003. Detection of endophytic fungi in *Festuca* spp. by means of tissue print immunoassay. *Plant Breeding 122*: 217-222.

Johnson, I.R.; Chapman, D.F.; Snow, V.O.; Eckard, R.J.; Parsons, A.J.; Lambert, M.G.; Cullen, B.R. 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New Zealand. *Australian Journal of Experimental Agriculture 48*: 621-631.

Kelly, S.; Smith, E.; Brazendale, R. 2011. Pasture renewal in the Waikato and Bay of Plenty regions: an overview of farmer practice, experience and attitudes. *Pasture Persistence Symposium. Grassland Research and Practice Series 15*: 21-24.

Lee, J.M.; Thom, E.R.; Wynn, K.; Waugh, D.; Rossi, L.; Chapman, D.F. 2016. High perennial ryegrass seeding rates reduce plant size and survival during the first year after sowing: does this have implications for pasture sward persistence? *Grass and Forage Science*: early view online doi:10.1111/gfs.12243.

Lee, J.M.; Thom, E.R.; Chapman, D.F.; Wynn, K.; Waugh, D.; Rossi, L.; Faville, M.J.; Bell, N.L.; McNeill, M.R. 2018. High perennial ryegrass seeding rates do not negatively impact pasture sward persistence. *Grass and Forage Science* (submitted).

Macdonald, K.A.; Matthew, C.; Glassey, C.B.; McLean, N. 2011. Dairy farm systems to aid persistence. *Pasture Persistence Symposium. Grassland Research and Practice Series 15*: 199-210.

NIWA. 2017. Drought indicator charts. Accessed: 22/06/2017. https://www.niwa.co.nz/climate/information-and-resources/drought/charts

Parsons, A.J.; Edwards, G.R.; Newton, P.C.D.; Chapman, D.F.; Caradus, J.R.; Rasmussen, S.; Rowarth, J.S. 2011. Past lessons and future prospects: plant breeding for yield and persistence in cool-temperate pastures. *Grass and Forage Science 66*: 153-172.

Popay, A.J.; Hume, D.E. 2011. Endophytes improve ryegrass persistence by controlling insects. *Pasture Persistence Symposium. Grassland Research and Practice Series 15*: 149-156.

Reynolds, W.N. 2013. Addressing on-farm management to enhance pasture productivity and persistence. *Proceedings of the New Zealand Grassland Association 75*: 241-244.

Rijswijk, K.; Brazendale, R. 2016. Pasture renewal practices, experiences and attitudes: A comparison over time. *Journal of New Zealand Grasslands 78*: 51-56.

Scott, I. 2013. Innovation at Scott Farms, Tirau. *Proceedings of the New Zealand Grassland Association 75*: 67-70.

Stewart, A.V. 2006. Genetic origins of New Zealand perennial ryegrass (*Lolium perenne*) cultivars. *Advances in Pasture Breeding. Papers from the 13th Australasian Plant Breeding Conference. Grassland Research and Practice Series 12*: 55-61.

Thom, E.R.; Waugh, C.D.; McCabe, R.J. 1998. Growth and persistence of perennial and hybrid ryegrasses when grazed by dairy cows in the central Waikato region of New Zealand. *New Zealand Journal of Agricultural Research 41*: 477-486.

VSN International Ltd. 2011. GenStat for Windows, 14th Edition. VSN International Ltd., Hemel Hempstead, United Kingdom.