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Grazing and Soil Fertility Effect on Naturalized Annual Clover Species in New Zealand High Country☆,☆☆

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ABSTRACT

With a view to increasing rangeland pasture legume abundance, the herbage biomass and seedling recruitment of four New Zealand naturalized annual clover species (haresfoot clover *Trifolium arvense* L., suckling clover *T. dubium* Sibth, cluster clover *T. glomeratum* L., and striated clover *T. striatum* L.) were measured in relation to spring grazing deferment versus continuous grazing and low versus high superphosphate fertilizer application (5 vs. 9 kg P · ha^{-1}) at a midaltitude (700-m) hill site. Naturalized species were dominant over periodically sown white (*T. repens* L.) and subterranean clover (*T. subterraneum* L.), contributing > 90% to sward legume composition. Rainfall in spring–early summer varied greatly between years, driving the large variation in sward legume content (28% in the moist first year; 2% in the very dry second year). Grazing deferment in spring did not influence autumn seedling recruitment or the following spring herbage biomass of naturalized species. However, autumn recruitment of naturalized clovers was greater under low fertilizer (563 seedlings · m^{-2}) compared with high fertilizer application (271 seedlings · m^{-2}) in the second year of the study, suggesting a niche for these species under conditions of low soil P and S. Management efforts should focus on strategies to enhance naturalized species spread within NZ rangeland.

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Introduction

New Zealand (NZ) hill and high country rangeland soils are low in available nitrogen (N) (White, 1990). Pasture productivity is driven by N inputs sourced primarily from legumes and their biological N fixation (Haynes and Williams, 1993). NZ's traditional pasture improvement model of growing legume species (Bowatte et al., 2006) requires phosphorus (P), sulphur (S), and lime ($CaCO_3$) application to alleviate major native edaphic constraints (low pH [4.5–5.5] and available P and S) to the growth of legumes adapted to higher soil fertility such as white clover (*Trifolium repens* L.), (Moir et al., 2000). At annual rainfall totals below 800 mm per annum, moisture stress in summer restricts vegetative reproduction of white clover through stolons (Valentine and Matthew, 2000; Knowles et al., 2003).

Widely distributed across NZ's South Island hill and high country, the naturalized annual clover species (hereafter called naturalized species), haresfoot clover (*Trifolium arvense* L.), suckling clover (*T. dubium* Sibth), cluster clover (*T. glomeratum* L.), and striated clover (*T. striatum* L.), are commonly present to locally abundant in summer dry zones, especially on hill slopes with north-facing (sunny) aspects (Boswell et al., 2003; Maxwell et al., 2010). Increasing their abundance represents a management endeavor to raise the quality of the pasture resource. However, little is known of their biomass productivity in relation to key management factors such as fertilizer application and grazing management. Maxwell et al. (2012, 2013) reported small herbage dry matter (DM) responses by naturalized species to high P, S, and lime addition in climate-controlled studies. Field trial agronomic information on naturalized species would benefit grazing management in hill and high country rangeland areas.

Increasing the abundance of annual pasture species in areas that are normally under continuous grazing involves deferred grazing techniques to encourage production and fall of seed (Edwards et al., 2005), which can increase the productivity and persistence of legume species because of increased natural reseeding (Lowther et al., 1992; Ates et al., 2015). In order to quantify the effect of spring grazing deferment relative to continuous grazing and low versus high superphosphate (P and S) fertilizer application on naturalized species herbage production, seed production, and subsequent seedling recruitment, a 19-month field study was conducted within an extensively grazed hill pasture, typical of summer dry NZ South Island hill and high country rangeland.

Methods

The experiment was established at Mt Grand Station, a 2 131-ha commercial sheep and beef hill and high country farm operated by

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Lincoln University, located in Central Otago district, South Island (lat 44°38′01.93″S; long 169°19′42.89″E). The 65-ha hill paddock was on a north-facing hillside (sunny aspect) of moderate–steep (20–30°) slope at 700 masl. The sedimentary Arrow steepland soil (Pallic/Yellow-Grey Earth; USDA classification Fragiudalf) from schist and loess parent material (Duncan et al., 1997) had low pH_{H2O} (5.5), moderate plant-available P (Olsen P 18 mg · kg^{-1}) and low S levels (Sulphate-S 9 mg · kg^{-1}) measured at 0–7.5-cm soil depth (Edmeades et al., 2006; Morton and Roberts, 2012). Topography is mountain and valley rangeland vegetated with naturalized grasses, legumes, herbs, native tussocks, and remnant native shrub (Land Information New Zealand, 2006). Elevation ranges from 380–1400 masl, with a continental-like climate of hot dry summers and cold frosty winters. Long-term average annual rainfall (60 years) is 703 mm, with high annual and monthly variability (Fig. 1).

The paddock in which experimentation was undertaken was grazed continuously with 300 Merino ewes (lambing in late September) from spring to late summer (mid-September to February) at 4.6 ewes · ha^{-1}, resuming again from midautumn to midwinter (April—July) with both sheep (300 ewes and 4 rams) and cattle (mixed-breed beef heifers and steers).

From October 2008 to May 2010, grazing deferment and superphosphate fertilizer effect on naturalized species herbage biomass and reproduction were examined in a factorial split plot, randomized, complete block design, with three grazing treatment main plots (5 × 5 m) and two fertilizer treatment split plots (2.5 × 5 m) within main plots, replicated four times. Treatments were continuous grazing, early deferment (grazing ceased early–mid spring; October–November), and late deferment (grazing ceased late spring–early summer; November–December). Fertilizer was applied at low (75 kg · ha^{-1} of 30% sulphur superphosphate; 5 kg P and 23 kg S · ha^{-1}) and high (200 kg · ha^{-1} of 30% sulphur superphosphate; 9 kg P and 38 kg S · ha^{-1}) rates on 6 September 2008.

Pasture was harvested in spring (11 November and 2 December 2008; 18 November 2009), summer (27 January 2009; 10 March 2010), and autumn (6 May 2009; 26 May 2010) from two 0.2-m^2 quadrats within split plots. Sorted samples were oven-dried at 70°C for 48 hours and weighed to obtain DM values (% and kg DM · ha^{-1}) of clover species, grass, weed and herb, and dead matter components.

Clover seed present within herbage cuts was counted in Yr 1 (summer, 27 January 2009) when abundant flowering occurred. Seedling recruitment measurements were made in late autumn (6 May 2009; 26 May 2010) by counting seedling numbers present on twenty 6.1 cm diameter × 4.5 cm depth soil cores collected from split plots.

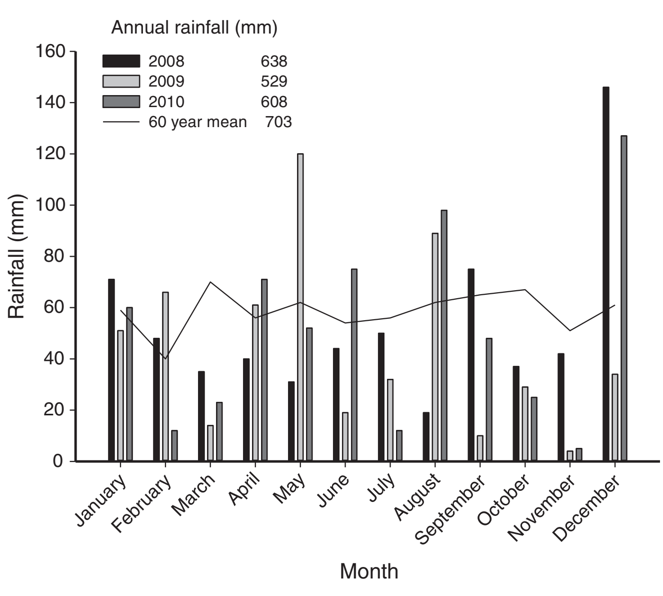

Figure 1. Annual and monthly rainfall during 2008, 2009, and 2010 at the midaltitude (700 m above sea level) high country hill site on Mt Grand Station, Central Otago, New Zealand. NB autumn (March–May), winter (June–August), spring (September–November), and summer (December–February).

Using GenStat 13 (Lawes Agricultural Trust, Rothamsted, UK), herbage DM of all botanical components (% and kg DM · ha^{-1}) was analyzed using a one-way analysis of variance (ANOVA) to determine any differences in both years. Effects of grazing deferment, SP fertilizer, harvest time, and their interactions were analyzed by conducting a split-split plot ANOVA for both years. Treatment effects on seed production and seedling recruitment were analyzed by conducting a split plot ANOVA at one date.

Results

Legume abundance contrasted strongly between years. Yr 1 naturalized and sown clover species biomass was 689 kg DM · ha^{-1} compared with 58 kg DM · ha^{-1} in Yr 2 (Table 1).

Naturalized species dominated the legume component of the hill pasture sward, contributing more biomass than white and subterranean clovers (see Table 1). Individual clover species order of abundance in Yr 1 was striated > cluster ≥ suckling > haresfoot, white and subterranean clovers ($P < 0.001$; see Table 1). Striated, cluster, and suckling clovers composed 50%, 26%, and 19% of sward legume biomass, respectively, in Yr 1 (see Table 1).

Seed production varied greatly among clover species. Cluster and striated clovers (2 455 and 1 330 seeds · m^{-2}, respectively) were greater ($P < 0.001$) than suckling, haresfoot, subterranean, and white clovers (310, 40, 2, and 10 seeds · m^{-2}, respectively).

Seedling recruitment of naturalized species in autumn (May) was more numerous in 2010 (417 seedlings · m^{-2}) than 2009 (167 seedlings · m^{-2}), ($P < 0.001$; see Table 1). White and subterranean clover recruitment was minimal. In autumn 2009, striated and suckling clovers showed the most seedling recruitment at 550 and 346 seedlings · m^{-2}, respectively, being greater than other species ($P < 0.001$; see Table 1). In autumn 2010, striated, suckling, and cluster clover recruitment increased considerably (see Table 1) and was greater than haresfoot, subterranean, and white clover recruitment ($P < 0.001$; see Table 1).

Grazing deferment in spring had no detectable influence on seed production (not shown) or subsequent autumn seedling recruitment of any clover species, in either year (see Table 1).

More seedling recruitment was observed under low superphosphate application (see Table 1). Seedling numbers in autumn 2010 were greater ($P < 0.001$) under low superphosphate (563 seedlings · m^{-2}) than high (271 seedlings · m^{-2}; see Table 1), reflecting the abundant seedling recruitment of three naturalized species in particular (striated, suckling, and cluster clover) under low superphosphate fertilizer application ($P < 0.001$; Fig. 2). Superphosphate fertilizer application did not influence herbage biomass in either year (see Table 1) or seed production.

Discussion

The reasons for greater naturalized species abundance compared with white and subterranean clover are partly phenological in nature. With lower base temperatures for germination and lower thermal time requirements for seedling emergence and seedling growth compared with white clover (Lonati et al., 2009), these annual plants complete their lifecycle (germinate, establish, grow, flower, and produce seed) before the onset of soil moisture deficits typical of sunnier northern aspects in late spring–summer (Lambert and Roberts, 1976), which are detrimental to white clover growth and stolon propagation. Subterranean clover has similar germination and seedling development characteristics to naturalized species (Lonati et al., 2009); however, the factors of high grazing preference (Hyslop et al., 2003) and continuous grazing pressure during the subterranean clover peak flowering period through spring (October–November) often prevent adequate seed

Table 1
Naturalized annual clover biomass and other pasture biomass components in Yr 1 (October 2008 — May 2009) and Yr 2 (November 2009 — May 2010) and clover species seedling recruitment in autumn (May) 2009 and 2010 in relation to spring grazing management (continuous, early spring deferment, late spring deferment) and superphosphate fertilizer application (low—75 kg · ha^{-1} and high—200 kg · ha^{-1} of 30% sulphur super) at the Central Otago site, New Zealand

	Biomass		Biomass		Seedling recruitment	
	(%)		(kg DM · ha^{-1})		(m^{-2})	
Botanical components	Yr 1	Yr 2	Yr 1	Yr 2	Autumn 2009	Autumn 2010
Naturalized annual clovers						
Trifolium arvense	0.4 a	0.01 a	12.6 a	0.3 a	4 a	31 a
T. dubium	5.7 b	0.1 a	125.7 b	1.8 a	346 b	1098 c
T. glomeratum	7.2 b	0.1 a	186.7 c	1.9 a	80 a	270 b
T. striatum	14.4 c	1.7 b	343 d	46.6 b	550 c	1181 c
Sown clovers						
T. repens	0.4 a	0.2 a	12.2 a	6.8 a	13 a	11 a
T. subterraneum	0.4 a	0.04 a	8.9 a	0.7 a	6 a	11 a
Total clover	28.4	2.15	689.1	58.1	167	417
LSD (5%)[1]	1.5	0.31	40.9	9.83	128	206
Significance[2]	***	***	***	***	***	***
Naturalized annual clovers	27.6 b	1.92 a	668 b	51 a	167	417
Grasses [3]	35.5 c	27.3 b	888 c	730 b	–	–
Weeds and herbs [4]	2.7 a	4 a	64 a	76 a	–	–
Dead	33.4 c	66.6 c	859 c	1570 c	–	–
LSD (5%)	4.6	3	140.8	152.4	na	na
Significance	***	***	***	***	na	na
Total pasture biomass			2500	2433		

	Naturalized annual clovers					
	Biomass		Biomass		Seedling recruitment	
	(%)		(kg DM · ha^{-1})		(m^{-2})	
	Yr 1	Yr 2	Yr 1	Yr 2	Autumn 2009	Autumn 2010
Grazing management						
Continuous	22.5	5.8	523	4	173	408
Early deferment	31	6	804	5.3	199	423
Late deferment	31.8	5.2	702	3.8	121	429
Significance	ns	ns	ns	ns	ns	ns
Superphosphate fertilizer						
Low	27.5	5	707	4.7	183	563 b
High	29.3	6.4	646	4	150	271 a
LSD (5%)	na	na	na	na	na	119
Significance	ns	ns	ns	ns	ns	***

[1] LSD, least significant difference; different letters denote means that are significantly different at 5% level.
[2] ***Indicates a significant difference between a clover species, botanical component group, or a treatment at $P \le 0.001$, ns = not significant and na = not applicable.
[3] Grass species present: Browntop *Agrostis capillaris* L., Kentucky bluegrass *Poa pratensis* L., Annual poa *Poa annua* L., Sweet vernal *Anoxanthum odoratum* L., Tall oat grass *Arrhenatherum elatius* L., Blue wheat grass *Elymus* spp., Danthonia grasses *Rytidosperma* spp., Perennial ryegrass *Lolium perenne* L., Cocksfoot *Dactylis glomerata*, Downy brome *Bromus tectorum* L., Ripgut brome *Bromus diandrus* Roth, Needle grass *Austrostipa nodosa*.
[4] Weed and herb species present: Mouse-ear hawkweed *Hieraceum pilosella*, Hawksbeard *Crepis capillaris* L., Storksbill *Erodium cicutarium*, Sheep's sorrel *Rumex acetosella*.

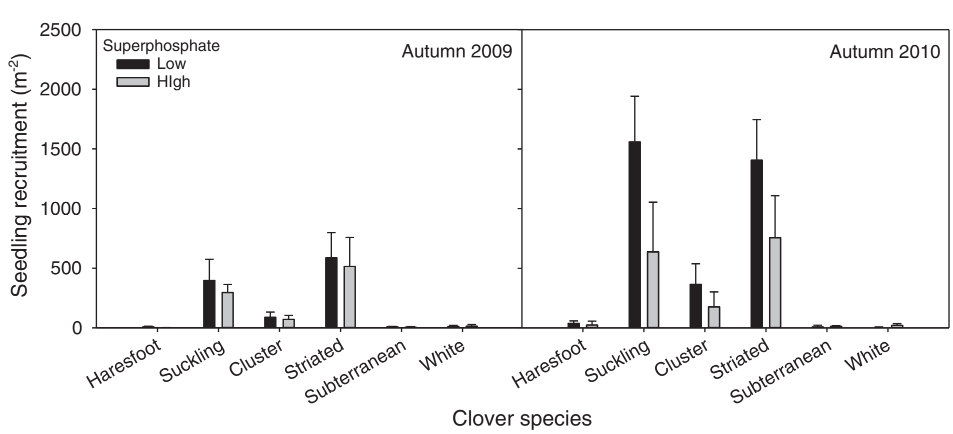

Figure 2. Influence of low (75 kg · ha^{-1}) and high (200 kg · ha^{-1}) superphosphate fertilizer application (30% sulphur super) on seedling recruitment (m^{-2}) of the six resident clover species in autumn (May) 2009 and 2010 at the Central Otago site, New Zealand. Error bars are ± standard error of the mean.

production for abundant seedling recruitment (Ates et al., 2015). Consequently, the abundance of naturalized species during moist years (November 2008–May 2009) and their persistence in dry years (November 2009–May 2010) is greater than white and subterranean clover at this north-facing site. These naturalized species appear more ecologically successful due to their regenerative ability (Lonati et al., 2009) and reproductive strategy (Norman et al., 2005) in this summer dry environment, despite periodic inputs of white clover seed from broadcast-over sowing every 3–5 yr.

The much higher biomass of naturalized species in 2008 than 2009 appears to have been strongly driven by higher spring and early summer rainfall quantity. Naturalized species herbage biomass (% DM and kg DM · ha^{-1}) was 14 times greater in Yr 1. September, October, November, and December rainfall in 2008 was greater at 75, 37, 42, and 146 mm, respectively, than during 2009 at 10, 29, 4, and 34 mm, respectively. September and November rainfall in 2009 was extremely low, being 84% and 92% less than the 60-yr average for those spring months, respectively. Hepp et al. (2003) attributed a 2.5-fold difference in legume abundance (white, subterranean, suckling, and cluster clovers) to higher soil moisture availability and more even rainfall distribution during the second season compared with the first in summer dry North Island east coast hill country.

Greater naturalized species seedling recruitment in autumn 2010 reflects two processes. First is the inhibiting influence litter layers can have on grassland species seedling recruitment (Jensen and Gutekunst, 2003). Sward dead matter content was large in autumn 2009 as a consequence of abundant herbage accumulation from the moist spring–early summer. Contrastingly, following a very dry midspring in Yr 2 and more typical summer dry period, considerable grass plant death would have occurred, leaving colonizing space for annual clovers and/or less competition from the remaining live grass component during autumn (Edwards and Crawley, 1999). Second, in dry grassland environments, there is a much smaller carry-over seed bank of grass species than annual clovers (Russi et al. 1992). A larger proportion of grass seed may have germinated in the first autumn owing to the mass of viable grass seed produced under the moist spring–early summer conditions. In the second autumn, fewer available grass seeds may have germinated from the bare soil surface seed bank, allowing more clover seedlings to occupy soil space and establish.

The reasons for a lack of effect from grazing deferment appear to be that 1) the naturalized species seed bank is high or at maximum already before our grazing deferment treatments being imposed and 2) the soil fertility factors of moderate soil P, low soil S (Maxwell et al., 2012, 2013), and reduced preferential grazing pressure on naturalized species from the onset of clover flower maturation (Thomas et al., 2010; Maxwell et al., 2015) appear to favor naturalized species abundance. In dry steep hill country pastures of Victoria in southern Australia (< 600 mm annual rainfall), deferred grazing did not have an effect on the resident legume species of subterranean and suckling clover (Nie and Zollinger, 2011).

Seedling recruitment of striated, cluster, and suckling clovers was significantly greater in low superphosphate application treatments. These species have a low nutrient requirement for optimum growth, specifically a low S requirement for optimum DM production (Maxwell et al., 2012), and are adapted to low soil P levels (Dodd and Orr, 1995). Under low to medium soil P fertility, the naturalized species showed optimum DM accumulation in a glasshouse trial (Maxwell et al., 2013). The available (Olsen) P level measured at this hill site was moderate, and the available (Sulphate) S level was low. Beale et al. (1993) reported striated and haresfoot clovers being restricted to light textured soils in Morocco, with striated clover being associated with very low P status soils. Maxwell et al. (2010) found greater striated clover herbage visual cover (%) associated with lower soil P levels within Mt Grand Station's middle–lower altitude range. However, no association was observed between striated, cluster, or suckling clover and soil S fertility level (Maxwell et al., 2010).

Implications

As naturalized species were dominant, management efforts should focus on strategies to enhance their spread within rangeland for the purposes of livestock spring feed and associated benefits of annual N-fixation inputs. Spring grazing deferment may have limited impact on enhancing seed production. Instead, grazing management might carefully target regrowth in autumn, where competition from perennial grass may limit clover establishment. This might include salt application to target grazing pressure on Na-deficient soils in inland areas (Tozer et al., 2013). Alternatively, grazing management could target moister-shady hill sides where white clover is more abundant and would benefit from reduced grass cover in autumn. The phosphorus and sulphur nutrient requirements of naturalized species are low, indicating that superphosphate fertilizer applications could be reduced to support naturalized species abundance. The long-term sustainability of extensive grazed agroecosystems will depend on greater nutrient (i.e., P) efficiency, involving sustained production with reduced fertilizer inputs.

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References

Ates, S, Lucas, RJ, Edwards, GR, 2015. Effects of stocking rate and closing date on subterranean clover populations and dry matter production in dryland sheep pastures. New Zealand Journal of Agricultural Research 56, 22–36.
Beale, PE, Bounejmate, M, Lahlou, A, Marx, DB, Christiansen, S, 1993. Distribution of annual *Trifolium* species in Morocco. Australian Journal of Experimental Agriculture 44, 1303–1310.
Boswell, CC, Lucas, RJ, Lonati, M, Fletcher, A, Moot, DJ, 2003. The ecology of four annual clovers adventive in New Zealand grasslands. In: Moot, D.J. (Ed.), Legumes for dryland pastures. Proceedings of the New Zealand Grassland Association Symposium, Grassland Research and Practice Series; No. 11; 18–19 November 2003. Lincoln University, Canterbury, NZ, pp. 175–188.
Bowatte, S, Russell, T, Carran, A, Gillingham, AG, 2006. Can phosphorus fertilizers alone increase levels of soil nitrogen in New Zealand hill country pastures? Nutrient Cycling in Agroecosystems 75, 57–66.
Dodd, MD, Orr, SJ, 1995. Seasonal growth, flowering patterns, and phosphate response of 18 annual legumes grown in a hill country soil. New Zealand Journal of Agricultural Research 38, 21–32.
Duncan, R, Lucas, RJ, Palmer, C, 1997. Mt Grand Station: baseline survey of the vegetation and soils. Department of Plant Science, Lincoln University, Canterbury, New Zealand (40 p).
Edmeades, DC, Metherell, AK, Waller, JE, Roberts, AHC, Morton, JD, 2006. Defining the relationships between pasture production and soil P and the development of a dynamic P model for New Zealand pastures: a review of recent developments. New Zealand Journal of Agricultural Research 49, 207–222.
Edwards, GR, Crawley, MJ, 1999. Effects of disturbance and rabbit grazing on seedling recruitment of six mesic grassland species. Seed Science Research 9, 145–156.
Edwards, GR, Hay, MJM, Brock, JL, 2005. Seedling recruitment of forage and weed species under continuous and rotational sheep grazing in a temperate New Zealand pasture. Grass and Forage Science 60, 186–199.
Haynes, RJ, Williams, PH, 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy 49, 119–199.
Hepp, C, Valentine, I, Hodgson, J, Gillingham, AG, Kemp, PD, 2003. Effects of grass suppression on legume abundance during two contrasting seasons on a summer-dry hill country site. In: Moot, D.J. (Ed.), Legumes for dryland pastures. Proceedings of the New Zealand Grassland Association Symposium, Grassland Research and Practice Series; No. 11; 18–19 November 2003. Lincoln University, Lincoln, Canterbury, NZ, pp. 123–129.
Hyslop, MG, Slay, MWA, Moffat, CA, 2003. Dry matter accumulation and sheep grazing preference of six winter active annual legumes. In: Moot, D.J. (Ed.), Legumes for dryland pastures. Proceedings of the New Zealand Grassland Association Symposium, Grassland Research and Practice Series; No. 11; 18–19 November 2003. Lincoln University, Canterbury, NZ, pp. 117–122.
Jensen, K, Gutekunst, K, 2003. Effects of litter on establishment of grassland species: the role of seed size and successional status. Basic and Applied Ecology 4, 579–587.
Knowles, IM, Fraser, TJ, Daly, MJ, 2003. White clover: loss in drought and subsequent recovery. In: Moot, D.J. (Ed.), Legumes for dryland pastures. Proceedings of the New Zealand Grassland Association Symposium, Grassland Research and Practice Series; No. 11; 18–19 November 2003. Lincoln University, Lincoln, Canterbury, NZ, pp. 37–42.
Lambert, MG, Roberts, E, 1976. Aspect differences in an unimproved hill country pasture. 1. Climatic differences. New Zealand Journal of Agricultural Research 19, 459–467.

Land Information New Zealand, 2006. Department of Conservation Resources Report on Tenure Review of Mount Grand Pastoral Lease. Available at: http://www.linz.govt.nz/sites/default/files/docs/crownproperty/high-countryleases/lease list/mt-grand-crr-pt1.pdf (Accessed 5 December 2012).

Lonati, M, Moot, DJ, Aceto, P, Cavallero, A, Lucas, RJ, 2009. Thermal time requirements for germination, emergence and seedling development of adventive legume and grass species. New Zealand Journal of Agricultural Research 52, 17–29.

Lowther, WL, Weddernburn, ME, Trainor, KD, 1992. Reproductive phenology and natural reseeding of 'Grasslands Maku' *Lotus pedunculatus* in tussock grassland environments. New Zealand Journal of Agricultural Research 35, 157–162.

Maxwell, TMR, Moir, JL, Edwards, GR, 2010. Influence of environmental factors on the abundance of naturalized annual clovers in the South Island hill and high country. Proceedings of the New Zealand Grassland Association 72, 165–170.

Maxwell, TMR, Moir, JL, Edwards, GR, 2012. Sulphur and lime response of four adventive annual clover species grown in a New Zealand high country soil under glasshouse conditions. New Zealand Journal of Agricultural Research 55, 47–62.

Maxwell, TMR, Moir, JL, Edwards, GR, 2013. Phosphorus response and efficiency of four adventive annual clover species grown in a New Zealand high country soil under glasshouse conditions. New Zealand Journal of Agricultural Research 56, 203–214.

Maxwell, TMR, Moir, JL, Edwards, GR, 2015. Grazing preference of Merino sheep for naturalized annual clover species relative to commonly sown clover species. Grass and Forage Science 71, 291–304.

Moir, JL, Scotter, DR, Hedley, MJ, Mackay, AD, 2000. A climate-driven, soil fertility dependent, pasture production model. New Zealand Journal of Agricultural Research 43, 491–500.

Morton, J., Roberts, A. (Eds.), 2012. Fertiliser use on New Zealand sheep and beef farms: the principles and practice of soil fertility and fertiliser use on New Zealand sheep and beef farms. New Zealand Fertiliser Manufacturers' Research Association, Auckland, New Zealand (Available at: http://www.fertiliser.org.nz/Site/resource_center/Booklets.aspx).

Nie, ZN, Zollinger, RP, 2011. Impact of deferred grazing and fertilizer on plant population density, ground cover and soil moisture of native pastures in steep hill country of southern Australia. Grass and Forage Science 67, 231–242.

Norman, HC, Cocks, PS, Galwey, NW, 2005. Annual clovers (*Trifolium* spp.) have different reproductive strategies to achieve persistence in Mediterranean-type climates. Australian Journal of Agricultural Research 56, 33–43.

Russi, L, Cocks, PS, Roberts, EH, 1992. The fate of legume seeds eaten by sheep from a Mediterranean grassland. Journal of Applied Ecology 29, 772–778.

Thomas, DT, Milton, JTB, Revell, CK, Ewing, MA, Dynes, RA, Murray, K, Lindsay, DR, 2010. Preference of sheep among annual legumes is more closely related to plant nutritive characteristics as plants mature. Animal Production Science 50, 114–123.

Tozer, KN, Marshall, AJ, Cameron, CA, Edwards, GR, 2013. Salt (NaCl) application as a tool to reduce the annual weed, ripgut brome, in New Zealand hill/high country pastures. New Zealand Journal of Agricultural Research 56, 117–129.

Valentine, I, Matthew, C, 2000. Plant growth, development and yield. In: White, J., Hodgson, J. (Eds.), New Zealand pasture and crop science 1990. Oxford University Press, Oxford, England, pp. 11–29.

White, JGH, 1990. Hill and high country pasture. In: Langer, R.H.M. (Ed.), Pastures; their ecology and management 1990. Oxford University Press, Oxford, England, pp. 299–336.