The ecology of four annual clovers adventive in New Zealand grasslands

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Abstract
Four annual clovers have become adapted to the dry and semi-arid grasslands in New Zealand. In the absence of competition from perennial clovers, which are adapted to sub-humid and humid environments, further spread is likely to continue. Annuals rely on high numbers of small and hard seeds for survival. Their germination is dependent on a combination of adequate soil moisture and favourable temperatures, with no evidence of a prechilling treatment required. For striated clover, germination results highlight their adaptation to cool moist autumn conditions during germination. The benefits of adventive clovers for N fixation (0.2-100 kg N ha^{-1}) are greatest where sulphur fertiliser has been applied, the clover population is dense, and soil moisture ideal over several months, but may be nil in drought conditions.

Key words: annual clovers, germination, nitrogen fixation, semi-arid grassland, *Trifolium arvense*, *T. dubium, T. glomeratum, T. striatum*

Introduction
Approximately 20 annual clovers are established in New Zealand (Scott 2003). Subterranean clover (*Trifolium subterraneum*) is the most important annual clover species in dryland environments, but it is regarded as a sown species in developed pastures rather than an adventive species. Our focus on adventive species is therefore on the most common non-commercial annual clovers: suckling clover (*T. dubium*), cluster clover (*T. glomeratum*), striated clover (*T. striatum*), and haresfoot clover (*T. arvense*), which were described by Healy (1982).

At a time when the emphasis was on nationwide pasture improvement, Saxby (1956) reviewed pasture plants in New Zealand, and considered adventive clovers to be among the pasture plants "about which little good could be said". Similarly, Crawford (1984) included all four species in his list of 46 species of annual *Trifolium* that had low potential as pasture plants in Australia, and were given no other mention in his review. Recent publications (e.g. Fortune *et al.* 1995; Smith *et al.* 1995) indicate that Australian opinion of cluster clover has changed and that it is now recognised as having an important role in Australian agriculture.

The objective of this paper is to review current knowledge on the biology and distribution of the four adventive annual clovers in dryland grasslands of New Zealand. The main attribute of adventive annual clovers in New Zealand is the same as other grassland legumes - to fix atmospheric N into plant N. This improves overall pasture quality and increases the N available to other plants.

Ecological strategies of annual clovers
Annual clovers are probably most competitive in New Zealand's semi-arid environments, which are in the rain shadow of the alpine ranges, inland, above 350 m a.s.l., and have warm summers and cold winters. Annual clovers are also found in dry environments on the northern faces of hill country in both islands and on eastern lowland shallow, stony soils from Hawke's Bay to North Otago.

Carter (1984) listed the characteristics of the most successful annual plants, including annual clovers, 1) germinate rapidly; 2) emerge rapidly; 3) have a prostrate growth habit to avoid the full effects of grazing; and 4) set large numbers of small seeds under normal grazing and seasonal conditions. Subterranean clover has a contrasting strategy of producing fewer, much larger seeds contained in burrs buried in the soil. Carter *et al.* (1982) considered seed production and hard-seededness to be crucial parameters for persistence of annual legumes. Successful pasture legumes often have very small seeds that allow greater survival during passage through the digestive tract of sheep (Thomson *et al.* 1990; Russi *et al.* 1992). Thomson *et al.* (1990) further indicated that passage of seed through the intestines of grazing animals appeared to break down some of the effects of hard-seededness and assisted subsequent germination rates. However, Ghassali *et al.* (1998) found ingestion had little effect on the hardness or viability of most of the clover legume seeds they tested. The danger with small seeds is that they may be buried too deeply and fail to germinate, emerge and establish. This is more likely to be a problem in cultivated land. Seed sizes recorded for the clovers are shown in Table 1. Of the four species discussed in this paper, striated clover is the exception to the small seed rule.

Table 1 Seed sizes of four annual clovers adventive in New Zealand, with subterranean and white clover as reference species.

Species of *Trifolium*	Seed weight (mg)	Seed diameter (mm)
T. arvense (haresfoot)	0.23-0.44	< 1.0
T. dubium (suckling)	0.42	1-1.5
T. glomeratum (cluster)	0.33	< 1.0
T. striatum (striated)	2.0	1.5-2.0
T. subterraneum (subterranean)	4.3-12.40*	>2.0
T. repens (white)	0.6	1.0

*Dependent on cultivar. (Sources: Fortune *et al*. 1995; Webb *et al*. 1988; and Lonati unpublished data).

All four adventive annual clovers are aerial seeders and their numerous, generally small seeds (Table 1) are shed on to the soil surface in contrast to the relatively fewer, larger seeds of subterranean clover, a high proportion of which are buried in the soil where establishment will normally be more assured. Successful germination and establishment are then dependent on adequate soil moisture at an appropriate time. For example, there is huge variability between years in germination, productivity and N fixation with haresfoot clover (Table 2). In extremely dry years, the clover may not be evident on the landscape due to minimal germination; in moist seasons, whole hillsides may appear pink with *T. arvense* flowers during summer.

Subterranean clover relies on hard seed and high temperature dormancy to avoid false strike after summer rain and possible subsequent autumn drought. Like subterranean clover, striated clover in North Canterbury (Smetham 1980), and cluster clover in lowland stony shallow soils (Lucas unpublished) are winter active-they germinate in autumn, and grow through winter and grow especially well in spring. The other annuals, notably haresfoot clover, may germinate at any time when soil moisture and temperature conditions are favourable. With haresfoot clover and probably the other small-seeded species, germination in spring is more reliable than in autumn in semi-arid higher altitude New Zealand environments.

Germination

The timing and rate of germination are key factors in the autumn re-establishment of a competitive winter annual seedling. The annual variability in the onset of autumn rainfall means the ambient temperatures experienced by the seed will differ annually. Not all of these temperatures will contribute equally to the rate

Table 2 Effect of season, landscape, and sulphur fertiliser on total N fixation (kg N/ha/yr) by haresfoot clover in semi-arid tussock grassland.

Location	Landscape class	Dry season (2000-01)	Moderately moist season (2001-02)	Wet spring (1984)
Benmore	Low sunny toeslope	4.1[1]	20.7[2]	
Benmore	Low sunny 600 m	1.4[1]	19.2[2]	
Benmore	Top of catchment 900 m	0.2[1]	15.7[2]	
Omarama	Sunny fan (nil S/ha)		10.5[2]	
Omarama	Sunny fan (25 kg S/ha)		63.4[2]	
Benmore	Sunny fan (25 kg S/ha)			35-102[1]

Sources: [1]Boswell *et al*. (2003); [2]Boswell unpublished

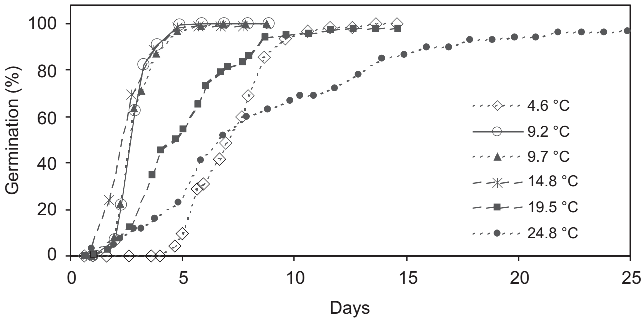

Figure 1 Germination (%) over time for *Trifolium striatum* (striated clover) seeds at different incubator temperatures.

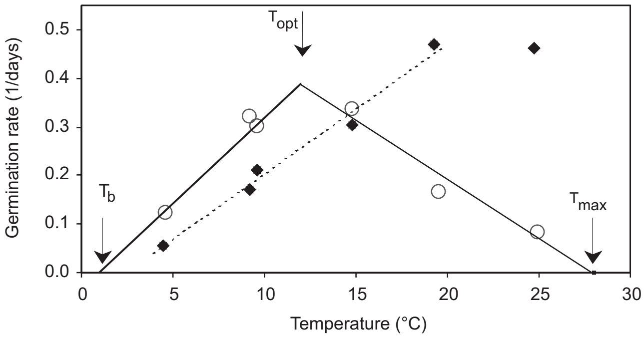

Figure 2 Rate of germination of *Trifolium striatum* (○) and *T. repens* (◆) at different temperatures. Base (T_b), optimum (T_{opt}) and maximum (T_{max}) temperatures are indicated for *T. striatum*. Regressions are: T_b to T_{opt} y = 0.0356 x - 0.0405 (R^2= 0.93) and T_{opt} to $T_{max,}$ y = 0.664 - 0.0239x (R^2 = 0.87).

of germination. To quantify the relationship between germination rate and temperature a series of experiments were set up at Lincoln University, Canterbury. Seed of the four adventive clovers and 'Mt Barker' subterranean clover, were all collected from a range of lowland and high country sites in the South Island. Seeds of each species were scarified, and then 50 seeds in each of three replicates were placed into petri dishes on moist blotting paper and incubated at measured temperatures of 4.6, 9.2, 9.7, 14.8, 19.5 or 24.8 °C. Analyses of results are ongoing, but those for striated clover are presented as an example of the relationships found.

The maximum number of seeds germinating was >95% at all temperatures (Figure 1). This indicates that no dormancy mechanism was operating, and that no prechilling or additional chemical treatment were required for maximum germination. Visible signs of germination differed between temperatures and was fastest at 14.8 °C, followed by the two 9.0 °C treatments. Germination was slowest for the 4.6 and 24.8 °C treatments.

These responses allow the cardinal temperatures for the species to be calculated (Moot *et al.* 2000) to show the germination response at any temperature, or range of temperatures experienced in the field (Figure 2). To do this, the rate of germination (1/number of days to 75% of the maximum germination) is regressed against the mean temperature for the increasing and decreasing portions of the linear response. The x-axis intercept of the positive regression indicates the base temperature (T_b), while the intercept of the negative regression indicates the maximum temperature (T_{max}). Below T_b and above T_{max}, no germination is expected. The optimum temperature for germination (T_{opt}) is interpolated from the intersection of the two regression lines, using 'broken stick' procedures (Draper and Smith 1998).

For striated clover T_b was calculated as 1.0 °C, but this was not significantly different from 0 °C. The calculated T_{max} was ~28 °C and T_{opt} was ~12.0 °C. The slope of the regression lines indicates the total thermal time required for germination (Moot *et al.* 2000), and this was estimated as 28 °Cdays for the suboptimal temperatures (T_b to T_{opt}) and 42 °Cdays for the supraoptimal (T_{opt} to T_{max}). These values can be utilised for any site and season to give an indication of when striated clover can be expected to germinate after autumn rain. For example, germination would be expected within 2 days at a mean soil temperature of 14 °C, but after 7 days at 4 °C or 5.5 days at 20 °C. The low optimum and T_{max} temperatures highlight striated clover's adaptation to cool moist conditions and high temperature dormancy. In contrast, T_{opt} for white clover appears to be ~25 °C (Figure 2) with a fast rate of germination still observed at 30 °C, the highest temperature tested by Moot *et al.* (2000).

Tolerance of cold and moisture stress

Caradus (1995) examined the tolerance (leaf survival) of 13 *Trifolium* species to single frost events of varying severity in a controlled environment room in which the tops but not soil and roots were subjected to frosts down to -16 °C. Haresfoot and suckling clovers were tolerant of frost, but cluster and subterranean clover were among the most frost-sensitive species. Striated clover was intermediate in its responses. However, Smetham (1968) reported only slight leaf damage after -10 °C frosts in grazed subterranean clover-based pastures at Wanaka. At Lincoln University's Mount Grand Station, Hawea, there appears to be a separation of species frequency on north faces according to altitude. Suckling clover is present above 900 m, cluster and striated clover are present below this and subterranean clover rarely occurs above 800 m (D. Power, personal communication). Haresfoot clover occurs at the driest sites, which generally occur at lower altitudes. Except for haresfoot clover, these distribution patterns follow the expected tolerances to increasing coldness with altitude. Ehrman & Cocks (1990) showed that the distributions of cluster, haresfoot and subterranean clovers in Syria were governed by differences in environments. They found haresfoot clover better adapted to lower rainfall (400-520 mm yr^{-1}) and extreme temperature environments (cold inland mountains and hot plains) compared with cluster and subterranean clover. Results from a survey across Morocco by Beale *et al.* (1993) showed temperature had little effect on clover species distributions compared with rainfall. Haresfoot clover was present at low rainfall sites (575 mm), striated clover at higher rainfall sites (773 mm), and cluster and subterranean clover adapted to intermediate rainfall sites (685 and 670 mm, respectively). Cluster clover appeared to be adaptable to a wide range of environmental conditions.

N fixation

Mean annual amounts of N fixed by legumes in typical New Zealand pastures ranged from 34 kg N ha^{-1} yr^{-1} on browntop-dominant (minimal clover) hill sites at 'Ballantrae' Research Station, Manawatu, to 342 kg N ha^{-1} yr^{-1} at warm and humid Kaikohe, Northland (Hoglund *et al.* 1979). These rates primarily measured perennial clover species N fixation.

Measurement of N fixation by annual clovers in New Zealand has been sporadic and limited in dry environments. Brock (1973) compared N fixation by pure stands of suckling clover with white clover at Palmerston North in nil–added P and very high P (100 kg P/ha/year) treatments. The amount of N fixed was measured as the mean annual amount of increased N in the herbage plus soil. Suckling clover fixed approximately half that of white clover (265 kg N ha^{-1}) at high P and also at nil P (195 kg N ha^{-1}), compared with 570 and 400 kg N ha^{-1} from white clover.

Annual quantities of N fixed by annual clovers will normally be less than perennial clovers because of the shorter growth period available in dry environments. Perez-Corona & Bermudez-de Castro (1999) measured N fixation rates of 10 legume species, including suckling clover, cluster clover, haresfoot clover and subterranean clover, using an acetylene reduction assay at the time of peak growth in late spring (May). Haresfoot clover had the highest N fixation activity. Boswell *et al.* (2003) measured N fixation of up to 63 kg N ha^{-1} from haresfoot clover in the period from germination in mid-October to harvest 3 months later in mid-January.

Haresfoot clover, which grows in semi-arid parts of New Zealand, fixes N at the limits of plant growth conditions. Holter (1978), using an acetylene reduction assay, found that N fixation by haresfoot clover grown on sand ceased only when soil moisture was very near wilting point.

In field experiments N^{15} has been used to provide a quantitative measure of the rates of N fixation of haresfoot clover in semi-arid tussock grassland near Omarama. Nitrogen fixation rates were correlated with plant growth, which was related to rainfall in spring and summer (Table 2). Boswell *et al.* (2003) reported mean N uptake, the proportion of N fixed, and the quantities of N fixed on different parts of a catchment in the relatively dry 2000-2001 growing season. Haresfoot clover N derived from N fixation on all the landscapes ranged from 83% to 89%. The quantity of N fixed on different parts of the landscape varied between landscape classes and within them primarily due to differences in abundance of haresfoot clover.

The importance of rectifying soil sulphur deficiency for nitrogen fixation in the semi-arid environment is also shown in Table 2. Boswell *et al.* (2003) reported results from a 1984–85 study where application of 25 kg ha^{-1} of S in any of four forms of fertiliser encouraged haresfoot clover growth, while no clover was apparent in a nil S control treatment. Nitrogen fixed by haresfoot clover ranged from 35-102 kg N ha^{-1} depending on the form of fertiliser, was recorded in a particularly moist growing season. Similarly, during 2001–2002, the addition of 25 kg S ha^{-1} produced a large increase in N fixed by haresfoot clover (from 10 to 63 kg N ha^{-1}, Table 2). In more moist environments, soil phosphorus deficiencies also need to be overcome for maximum clover growth (e.g. Brock 1973).

Rhizobia
Carter (1984) stressed the importance of the effectiveness of legume nodulation, and supplying appropriate rhizobia to particular legumes, for N fixation. No research has been conducted on the specific rhizobia requirements of these four annual clovers in New Zealand. However, clover rhizobia are widespread in New Zealand soils and rhizobia effective with annual clovers are the norm in drier soils (Greenwood & Pankhurst 1976).

Plant characteristics
Plant characteristics of the four clovers and their habitat ranges are summarised in Table 3.

Biomass/productivity:
There is limited information on adventive clover biomass productivity. This is in part because annual clovers are expected to grow in conditions that are suboptimal for white clover production. The maximum biomass of haresfoot clover recorded in field measurements in New Zealand was 3 300 kg DM ha^{-1} (Boswell *et al.* 2003). This measurement was recorded at discontinuous patches of dense haresfoot clover in an abnormally moist growing season in a semi-arid environment. Production of suckling clover (Brock 1973) at Palmerston North at low phosphorus ranged from 3 130 to 5 100 kg DM ha^{-1} in a pure sward (white clover ranged between 4 790 and 8 290 kg DM ha^{-1}). Williams *et al.* (1980) compared the productivity of suckling clover and cluster clover with white clover at two and three North Island sites, respectively. Suckling clover yielded 77% and cluster clover 90% of white clover. Lambert *et al.* (1986) found that in optimal conditions in North Island hill pastures (sunny NW slope during spring), suckling clover produced approximately 70% of the biomass of white clover at the same site and time. In contrast, subterranean clover outproduced white clover at two of the three sites reported by Williams *et al.* (1980). In an outdoor experiment using soil cores of low fertility hill soil, Dodd & Orr (1995) measured the equivalent of 850 kg DM ha^{-1} from haresfoot clover compared with 3100 kg DM ha^{-1} from subterranean clover. Similarly, cluster clover in pot trials produced 25% less biomass than subterranean clover (Blair & Cordero 1978).

Flowering
The timing of flowering follows leaf production in clovers, but Palmer (1972) found that time of flowering in haresfoot clover varied between plants both from within a collection site and between sites. Differences could not be explained in terms of environmental factors. In a semi-arid environment, peak flowering of haresfoot clover occurs in November. As with the other small-seeded annuals, each flower produces a single-seeded pod (Table 3). Haresfoot clover flowers continue to develop on the flower head, while ripe seed may be shed from lower on the flower head. A large proportion of the fresh seed is hard and will not germinate unless it is scarified. Saleem & Gliddon (1989) found that populations of haresfoot clover were self-compatible and were capable of inbreeding, which is an advantage for plant survival in harsh environments. Similarly, Palmer (1972) showed that reproduction in haresfoot clover was predominantly by self-pollination and between closely related individuals. In contrast, red and white clovers were both obligate outbreeders between populations of plants (Saleem & Gliddon 1989). Suckling clover produces yellow flowers from October to June depending on habitat and season (Webb *et al.* 1988), but peak flowering occurs in November in a moist environment (Caradus & Mackay 1989).

Cluster clover flowering peaked in late November 2002, after 'Denmark' subterranean clover, at Ashley Dene (11 m a.s.l.) on a stony silt loam soil near Lincoln, Canterbury (Lucas unpublished data).

Nutritional value
Tannins are present in relatively few species of herbaceous legumes (Bate-Smith 1973; Jones *et al.* 1973; Fay & Dale 1993). However, they were present (e.g. as flavolans = condensed tannins) in the haresfoot and suckling clovers studied by Sarkar *et al.* (1976). Flavolans were not found in leaves of red and white clovers. All flavolans were proanthocyanidins (Sarkar *et al.* 1976). Jones *et al.* (1973) recorded the presence of flavolans in haresfoot clover, but not in the other three adventive annuals, in their rapid screening test of 44 *Trifolium* species. The tannins produce astringency in the plant material and may reduce its palatability to grazing animals. This could inhibit grazing (e.g. Scott *et al*. 1995) and increase the likelihood of successful seed production. Despite this, Hughes (1975) found that haresfoot clover was a preferred plant of merino sheep in grazed tussock grassland, while Reddiex (1998) has shown that it was also a species preferred by rabbits in the same Mackenzie Basin, South Island environment. Both of these authors measured preference from the frequencies of plant fragments in dung, thus gaining

Table 3 Summary details of leaf and flower structures, plant form and geographical range of four adventive annual clovers in New Zealand.

	T. arvense	**T. dubium**	**T. glomeratum**	**T. striatum**
Leaflets	Soft greyish hairy leaflets	Hairless to slightly hairy; leaflets often reddish	Hairless	Densely hairy; light green colour
	Narrow leaflets	Stalk of central leaflet longer than others; some leaflets notched	Leaflets small, 3–12 mm long; some have single light or dark spot on leaves	Leaflets short-stalked, at times diamond-shaped, elongated 5-20 mm
Stems	Often reddish, wiry stems	Stems many, thin, wiry	Wiry, prostrate, scrambling	Stems hairy
Flower heads	Soft, hairy, pinkish, cylindrical; mainly at end of stem; many	5–12 flowers/head; flowers in leaf axils	Small globe-shaped heads; not stalked; in leaf axils	Egg-shaped heads 1.8 cm long; not stalked; at end of branches and in leaf axils - enlarged stipules at axes
Flowers	Flowers pink-white, in distance flowers look like pink haze. Flowers Aug-May depending on habitat and season	Yellow flowers; flowers Oct-June depending on habitat and season; peak flowering Nov in most environment	Pink/purplish flowers, small. Flowers Nov-March depending on habitat and season	Flowers longer than calyx. Calyx ribbed, toothed, prickly
Plant form	Varies from single stem (10 cm tall; single flower head) to a plant with many stems and heads, 30cm across, 30 cm tall; form depends on habitat condition	Few stems to many. circular prostrate form to semi-erect to scrambling form under favourable conditions; form depends on habitat conditions	Varies considerably in size with habitat condition	Prostrate in dry places; more erect in moister places
Plant characteristics	Germinates when moisture/ temperatures are satisfactory, mainly spring	Winter active North Island; autumn germination	Germinates when moisture/ temperatures are satisfactory; autumn germination in Canterbury	Winter active N. Canterbury; autumn germination in dry places is short-lived; leaves wither and the prickly fruiting calyxs at nodes give feeling of cords with knots at intervals (hence knotted clover)
Range	Common to locally abundant in dry waste places, river beds, modified tussock grassland at low altitudes, pastures on light soils both islands	Common throughout New Zealand	Locally common at dry waste places and pasture and coastal areas in eastern areas of both islands to North Otago	Occasional to locally abundant in dry waste places and thin hill pastures, or light soils in both islands, epsecially drier east coast areas; and modified tussock grassland of east SI
	Competitive on driest soils (BGE=semi-arid soils)	Range of soils	Prefers sub humid climate YGE = pallic soils	Prefers sub humid climate YGE = pallic soils

little idea of the severity of grazing on plants. The natural spread of haresfoot clover in semi-arid areas of the South Island has occurred during the years of rabbit population control that enables plants to complete their life cycle before being grazed.

Discussion

The perceived agronomic value of different clovers in New Zealand agriculture has changed with our history. Most New Zealand soils were not naturally fertile prior to European settlement, and legumes were an important fertility-building component of grassland soils. As fertility levels increased emphasis shifted to the more productive (usually perennial) clover species in sown mixtures. These proved to be better competitors than any resident annual species in most pastures. Annual clovers had a greater potential role to play in Australian pastures than they did in New Zealand because of the former's huge areas of moisture-deficient grassland. In New Zealand, annual clovers persist where there is regular moisture deficiency, such as on shallow, stony lowland soils, dry north–facing hills and the inland South Island semi-arid soils (previously known as brown-grey earth [BGE] soils; Hewitt 1998).

Reviews of the range of environments in which annual adventive clovers grow in New Zealand and Australia are found in Saxby (1956) and Ellis *et al.* (1984). Sometimes descriptions of distributions are too generalised and sweeping. In New Zealand hill country in particular, pastoral landscapes are highly variable and different species may survive in different parts of a given geographical location. Carter (1984) recognised the variability of pastoral landscapes in his conclusion that "In southern Australia there should be more emphasis on broad mixtures of species and cultivars to fit ecological niches and to cope with the uncertainty of the rainfall". We come to a similar conclusion with respect to clovers for dry to semi-arid New Zealand grassland.

The greatest continuing need for annual clovers is likely to be on dry hill land that will never be irrigated. A feature of New Zealand hillsides is variability in micro topography and the associated variability in water uptake after rainfall and loss by evapotranspiration. One consequence of this is the formation of small niches into which different annual clover species with slightly different moisture requirements/growth habits/seeding abilities may fit. If the full range of adventive species is present, they can provide increased clover growth and N fixation over a range of microsites with differing microclimates.

Suckling clover is the most common and widespread annual clover in New Zealand (Table 3). Its potential range is from warm, moist North Island hill country to high altitude tussock grassland up to 1000 m, but it cannot withstand semi-arid conditions. Historically, there was widespread use of suckling as a pioneer clover on sites that subterranean and white clovers now occupy. On the dry Canterbury Plains at Winchmore, Rickard (1972) found that suckling clover replaced white clover in unirrigated pasture. Suckling clover is better adapted to microsites where moisture stress is likely to be reduced. These include natural surface depressions where occasional rainfall may accumulate, or sites shaded or sheltered by adjacent rocks and/or other plants that reduce evapotranspiration losses. It succeeds on land with natural fertility levels too low to support white clover. However, it prefers moderate soil fertility relative to that tolerated by haresfoot clover (Scott *et al.* 1995).

Cluster clover has similar moisture requirements to suckling clover but grows better at the warmer end of suckling clover's temperature range. Cluster clover is common chiefly from Marlborough northward, but is also common at lower latitudes at Mount Grand Station Hawea on north faces at 500 m, and on low stony soils in open pasture in the sub-humid environmental zones. At Lincoln University's Ashley Dene farm on the Canterbury Plains, it dominated ryegrass/subterranean clover pastures by early summer after intensive spring set–stocking. Cluster clover is similar to suckling in nutrient requirements (i.e. can tolerate lower fertility); it volunteers on shallow open soils and is regarded as a useful producer on second-class sand country.

Saxby (1956) considered that striated clover has the same habitat range as cluster clover and has a similar agricultural significance as cluster and suckling clovers. In Australia, striated clover is usually found in association with subterranean clover in districts with adequate rainfall and the damper parts of dry districts. Striated clover is not as common as cluster or suckling clovers in New Zealand, but is common on much North Island hill country. It is the least common of the clovers at Mount Grand Station. Striated clover has a larger seed than the other three species (Table 1), which may affect its ability to establish in dry sites where smaller–seeded species succeed. We see it in a supplementary role to suckling clover and subterranean clover, occupying the less moisture–constrained microsites in warmer sub-humid hill grasslands.

Haresfoot clover persists in semi-arid environments, as well as in disturbed areas in low fertility lowland sites. Its distribution is best correlated with the distribution of semi-arid soils and adjacent pallic soils. These typically feature a dry, seasonally cold environment. Haresfoot clover is also more tolerant than other species of cold conditions and possibly of out-of-season frosting. Where it is present, haresfoot is continually increasing its range and altitude up to 1000 m. As with all legumes, it responds to applied fertiliser, especially to sulphur in dry, sulphur-deficient inland soils, and to the accumulation of nutrients at stock camps, often at high parts of hill blocks.

In dry sub-humid grassland a combination of the four adventive annual clovers with subterranean clover will be the most productive. The presence of combinations of suckling, cluster, striated, and haresfoot clovers can be used as indicators of where subterranean clover should be successful, as it may be restricted to suitable microsites within the landscape. Where haresfoot is the only clover present, subterranean clover may be unsuccessful, because the site is likely to be too dry and/or cold for it.

The four adventive species are unlikely to be sown, and therefore will continue to depend on natural spread. The effectiveness and spread of haresfoot clover will be encouraged by continued control of rabbit populations and by fertiliser, especially sulphur fertiliser, in semi-arid environments. Apart from the reported effect of intensive set-stocking on cluster clover at Ashley Dene, we know little of the effects of grazing animals and their management on the spread and productivity of annual adventive clovers.

Early New Zealand legume studies focussed on the role of legumes in fixing N for production by the grass component of pastures. More recently, interest is on the effect of legumes on feed quality and their effect on animal production. Our focus on the annual clovers for dry grassland is a return to studying the effects of N fixation for the grass component of the grassland. This is not only for the production of introduced grasses and the animals grazing them, but also for the survival and improved vigour of native species including short tussocks. Improved collective productivity of legumes and grasses should be managed to reduce the risk of native plant species loss, invasion by weed species, and soil loss through erosion on the dry grassland.

Conclusions

1) The four most common adventive annual clovers in New Zealand are adapted to sub-humid and semi-arid environments, which often have low natural fertility levels.
2) A mixture of annual clovers should allow the different species to establish at different microsites and result in increases in total N fixed.
3) In the short term, the presence/success of suckling, cluster and striated clovers at a site can indicate where subterranean clover could be successfully sown.
4) Where haresfoot is the only clover present, the site may be too dry and/or too cold for subterranean clover.
5) The spread of haresfoot and the other annual clovers should be encouraged to reap the ecosystem benefits of seasonally dependent pulses of fixed nitrogen.
6) Depending on environmental and management objectives, pulses of N input may be equally important for pasture productivity and for the survival and rejuvenation of native species, including short tussocks.

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