Pasture establishment on non-cultivable hill country: a review of the New Zealand literature

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Abstract

Steep, non-cultivable hill country below 1000 m comprises about 40% of New Zealand's land surface and is known as "hill country". It is used predominantly for mixed livestock farming, and makes a large contribution to the national economy. Recently there has been renewed interest by industry and government in germplasm introduction through pasture establishment to increase forage supply in these difficult environments. In this review, establishment is defined as development of a sown pasture species to a stage where it is able to reseed. The aim of this review was to determine the effect of key factors associated with pre-sowing management, sowing, and post-sowing management on establishment, including: site selection, herbicides, the role of litter, grazing management, burning, weed and pest control, fallow, fertiliser, species selection, seed quality, sowing time, sowing method, sowing rate, seed inoculation, coating and pelleting, natural reseeding and dissemination of seeds by animals. Over 120 studies were reviewed. A secondary aim was to highlight directions for future research.

Keywords: establishment success, sowing, pasture renewal, oversowing

Key messages:

- The amount and density of the resident vegetation at oversowing is one of the most critical factors influencing success of oversowing
- The variety of species and cultivars available enables selection of a seed mix tailored to site-specific conditions
- Future research needs include: strategies that reduce seedling desiccation during establishment, weed and pest control, establishment of forage herbs, legume establishment and reseeding, improving the evenness of distribution of aerially sown seed, and novel seed coating and pelleting techniques to enhance seed-soil contact.

Introduction

Steep, non-cultivable hill country below 1000 m comprises about 40% of New Zealand's land surface (Blaschke *et al.* 1992) and is known as "hill country". It comprises large tracts of land in the North and South Islands, much of which is used for mixed livestock farming, and makes a large contribution to the national economy. Extensive research in hill country on germplasm introduction using seed occurred in the 1980s/early 1990s. Recently, there has been renewed interest by industry and government in germplasm introduction to increase forage supply in these environments (Bray *et al.* 2013).

Seedling establishment has been defined in various ways, for example, by Charlton (1977) and Chapman *et al*. (1985). In this review, establishment is defined as *development of a sown pasture species to a stage where it is able to reseed* (which usually occurs within the first 12-18 months), and the review is limited mainly to New Zealand literature.

Establishment, survival, and growth of forages in hill country are governed predominantly by temperature, moisture, soil fertility, and plant management (Lambert *et al.* 1985; Scott *et al.* 1985; McKenzie *et al.* 1999). Whilst much South Island country originally in tussock grassland can be farmed at a range of soil nutrient states, North Island hill country is best farmed in a moderate to high fertility state to exclude or minimise re-invasion by scrub species (Scott *et al.* 1985; Krause *et al.* 1988; Blaschke *et al.* 1992; Bergin *et al.* 1995).

Apart from initial pasture development involving the clearance of scrub or bush and subsequent oversowing, the key options for increasing farm productivity on hill country are subdivision, topdressing with fertiliser or lime, management of livestock to ensure efficient and sustainable utilisation of forage, and introduction of new germplasm (Suckling 1966; Allan *et al.* 1985; Scott *et al.* 1985). If subdivision, topdressing and utilisation are advanced to the stage where further gains are sought, introducing new germplasm offers potential benefits of enhanced annual or seasonal production of forage, higher nutritive value of forage, and greater tolerance to factors such as drought, grazing, trampling, pests, or low fertility (Lambert *et al.* 1985). There is also the potential value of new germplasm to exploit the many different micro-sites present in hill pastures, and to allow for situations where the material was not introduced earlier, or was introduced but did not persist perhaps because of inappropriate management.

Many grass, legume, and herb species have been

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evaluated in hill country, particularly legumes to supply biologically fixed nitrogen to existing or introduced non-leguminous species (Suckling 1966; Chapman & Macfarlane 1985; Lambert *et al.* 1985; Scott *et al.* 1985). Methods for establishing species from seed on hill country largely depend on slope angle, accessibility and risk of erosion. On moderate to steep hill country e.g. >25^{o} slope angle, ground-based machinery is not able to be used safely for sowing species, requiring that seed be applied aerially using airplane or helicopter, or on the ground by hand or portable broadcast spinner. Utilising livestock to 'cultivate' the seedbed and aid in increasing seed-soil contact, and herbicides to kill or suppress the existing vegetation, are usually integral parts of the establishment process (Suckling 1966; Lambert *et al.* 1985; Hampton *et al.* 1999).

Establishment of seedlings on non-cultivable hill country is typically low due to many factors, including an inhospitable micro-climate with extremes of temperatures and moisture deficits, competition with existing vegetation, herbivory, and other factors. This may result in low germination, low emergence and low seedling establishment. For example, 4 months after sowing, only 7.6% of aerially sown seed and 7.9% of hand-sown seed established at Ballantrae in southern Hawke's Bay (Charlton 1977). In another study, 12-20% of perennial ryegrass (*Lolium perenne*) and cocksfoot (*Dactylis glomerata*) seeds germinated, but of the seeds that germinated, only 14 to 27% of them survived to the end of the first 12 months, depending on the species and site location (Cullen 1969). In a review, Campbell (1992) stated that the establishment of aerially broadcast viable seed usually ranges from 1 to 27% with a mean of 8%, which is much lower than establishment using conventional cultivation techniques. Further research is, therefore, required on methods that will result in increased establishment.

The following sections summarise and discuss the effect of key factors associated with pre-sowing management, sowing, and post-sowing management on establishment, including: site selection, herbicides, the role of litter, grazing management, burning, weed and pest control, fallow, fertiliser, species selection, seed quality, sowing time, sowing method, sowing rate, seed inoculation, coating and pelleting, natural reseeding and dissemination of seeds by animals. Directions for future research are highlighted.

Pre-sowing management

Site selection is influenced by climatic variables such as moisture, temperature and light, which all play critical roles in germination, seedling establishment and survival (Campbell & Swain 1973). Germinating seeds and seedlings are particularly vulnerable to desiccation (McWilliam *et al.* 1970; Gillingham 1973; Gillingham & Bell 1977), requiring management strategies to reduce moisture deficits during this vulnerable period. The combination of lack of effective moisture due to greater runoff and the vulnerability of a germinating seed to desiccation, may explain why moisture deficits are implicated as the main cause of mortality during germination and early seedling development (Campbell & Swain 1973; Campbell 1992). Steep hill country is also prone to greater runoff than flat or gently sloping land. North-facing slopes are typically hotter and drier than south-facing slopes; species must be chosen to suit these different environments. For example, potential evapotranspiration in March, June, September and December was greater on north- than south-facing slopes at Ballantrae in southern Hawke's Bay (Lambert & Roberts 1976). On north-facing slopes at Whatawhata (North Island moist hill country), moisture content in the top soil (0-7.5 cm depth) was below wilting point between January and March during a 3 year experiment (Gillingham 1973).

Herbicide is generally necessary for successful establishment of pasture species because other methods are unable to substantially reduce competition from the resident vegetation when oversowing. Campbell (1992) and Cullen (1971) concluded that the cover and density of the resident vegetation at oversowing was the most critical factor influencing success of oversowing - the greatest establishment occurs where the most weeds are killed for the longest period. Several herbicides have been investigated, including paraquat and diquat (e.g. Chapman *et al.* 1985; MacFarlane 1985), amitrole (e.g. Charlton & Henderson 1985), dicamba (e.g. Charlton & Henderson 1985), 2,2 DPA, 2,4-D (Dowling *et al.* 1971) and glyphosate (e.g. Chapman *et al.* 1985). MacFarlane (1985) found that herbicide impact was greater on the easy rather than steep slopes, possibly because of the greater effective land area of steep slopes when the steeper angle is taken into account. Another alternative hypothesis is that there is an interaction between the response of the plant to herbicide and climatic variables, such as soil moisture, which would vary according to slope. Note also that herbicide residual activity sometimes has detrimental effects on establishing seedlings (e.g. Baars *et al.* 1982) - timing of application is therefore critical.

Litter (dead matter) cover can assist germination by modifying the microclimate by reducing temperature extremes, increasing relative humidity and creating a soil surface that is more amenable for germination, as well as reducing seed predation (McWilliam & Dowling 1970; Campbell & Swain 1973; Baars *et al.* 1982). For example, Chapman & Fletcher (1985) found that seedling mortality was greatest where resident vegetation had been suppressed the most; up to 20% of seedlings died within 3 weeks of appearance in glyphosate-treated plots. They attributed this to factors that are more marked in exposed situations e.g. excessive bare ground, and damage from wind and surface drying. However, litter cover needs to be balanced against its potential to reduce seed-soil contact. There is little literature from New Zealand hill country determining the optimal cover and density of litter for germination and seedling emergence and survival. Slug abundance may also be enhanced by litter (Campbell & Swain 1973), but the effect of litter on predation by invertebrates other than slugs is poorly understood.

Hard grazing (e.g. to less than 2 cm in height) is used as an alternative to, or in conjunction with herbicide application to reduce competition from resident vegetation. In most cases, hard grazing is unable to reduce competition sufficiently to allow good establishment of broadcast seed (Chapman & Fletcher 1985; Campbell 1992). When combined with other strategies, such as treading of seed to increase seed-soil contact and herbicide application, hard grazing is effective (Sithamparanathan *et al.* 1986). Coarse salt application increases grazing intensity in localised areas because livestock crave salt which is often lacking in South Island hill country soils (Gillespie *et al.* 2006; Anderson *et al.* 2008). This enables resident vegetation to be heavily grazed, reduces competition, increases seed-soil contact and increases establishment of oversown species. For example, establishment of broadcast plantain (*Plantago lanceolata*) was much greater from swards to which salt had been applied than from swards that did not receive salt application (6.5 vs 1.1 seedlings/m^2, (Gillespie *et al.* 2006)). Hard grazing alone may be a useful strategy in tussock grasslands, where consideration must be given to the preservation of indigenous species.

While burning has been used extensively in hill country to remove resident vegetation and reduce competition, little research was found on this subject. Burning enhances herbicide action by removing litter (Sievwright 1957). Conversely, it also stimulates emergence from the weed seed bank and dries out and hardens the soil surface, making it more difficult for seed burial and penetration by young roots that are vulnerable to desiccation (Maret & Wilson 2005).

Fallow (cessation from grazing) can reduce tiller density through density dependent mortality, creating an open sward to assist in germination and establishment of oversown species. However, spring to autumn fallow can also enhance seed production of the resident vegetation, while a shorter fallow, applied up to seed development or after seed fall, can decrease tiller density while avoiding the negative impacts of seeding weedy species (Nie *et al.* 1997; Nie *et al.* 1999). A chemical fallow can also increase soil moisture and change the microclimate through litter creation, while effectively removing resident vegetation.

Nutrient cycling is particularly patchy and inefficient in hill country although non-limiting nutrients are required if new pasture species are to be introduced. A key to this is ensuring an efficient nitrogen cycle through developing a stable legume population (Levy 1970). Legume choice is therefore critical to successful pasture establishment in hill country.

Species

Pasture species commercially available vary in their adaptation to different hill country environments (Table 1). Legumes are difficult to establish by broadcasting because of epigeal germination in which the first leaves (cotyledons) are elevated above the ground as the juvenile stem (hypocotyl) elongates (Charlton 1977). This is in contrast to grasses which have hypogeal development where the cotyledon is not elevated and is less exposed to the elements. The different early seedling development patterns between grasses and legumes affect the ability of the radicle (precursor of primary root) to penetrate the soil surface - radicles of grasses penetrate the soil more rapidly during germination and are less prone to desiccation than those of legumes. For this reason litter can help reduce moisture deficits and increase germination of legumes in particular. In summer-dry North Canterbury, the presence of litter increased emergence by 4-fold in comparison to emergence from bare ground; the authors considered litter was essential for seedling establishment (Janson & White 1971). White clover (*Trifolium repens*) does not generally survive on dry, sunny, north-facing slopes; birdsfoot trefoil (*Lotus corniculatus*) or lucerne (*Medicago sativa*) may be better choices (Allan & Chapman 1987). However, lucerne seedlings are particularly prone to moisture deficits while establishing, and broadcasting is a high risk strategy for their establishment (Janson & White 1971). This may limit the use of lucerne in uncultivable hill country unless methods can be found that reduce moisture stress on seedlings as they emerge and develop. Red clover (*Trifolium pratense*) is best adapted to moist, cool locations while Caucasian clover (*Trifolium ambiguum*) is more drought-tolerant but often has low establishment (Rhodes & Clare 1983; Allan & Keoghan 1994; Moorhead *et al.* 1994). Subterranean clover (*Trifolium subterraneum*) is well adapted to summer-dry hill country where competition (shading) is removed before sowing and the species allowed to flower and set seed before summer drought (Smetham 2003a). Lotus (*Lotus pedunculatus*) is well adapted to acid soils (Scott & Mills 1980), which are prevalent at higher altitudes in New Zealand hill / high country. It also establishes well in low phosphate soils

Table 1 Guide to suitability of common pasture species for New Zealand environments and key papers on the establishment of common pastures species in hill country. A scale of 1 to 5 is used, where 1 = low and 5 = high suitability (criteria and rankings adapted from page C-38, Fleming 2003).

Pasture species	Moist hill country	North Island dry hill country	South Island dry hill or high country	Key references
Grasses				
Lolium perenne (perennial ryegrass)	3	2	1	(Falloon & Charlton 1984; Chapman *et al.* 1985; Barker & Zhang 1988; Wedderburn *et al.* 1989; Wedderburn *et al.* 1990; Wedderburn & Pengelly 1991; Moloney *et al.* 1993; Wedderburn *et al.* 1996; Rolston *et al.* 2000; Kemp *et al.* 2005)
Dactylis glomerata (cocksfoot)	5	5	4	(Allan 1985; Barker *et al.* 1985; Chapman *et al.* 1985; Allan 1986; Chapman & Campbell 1986; Allan & Chapman 1987; Barker & Zhang 1988; Scott *et al.* 1995; Kemp *et al.* 2005)
Festuca arundinacea (tall fescue)	1	1	2	(Charlton *et al.* 1986; Barker *et al.* 1993; Moloney *et al.* 1993; Allan & Keoghan 1994; Scott *et al.* 1995; Kemp *et al.* 2005)
Bromus wildenowii (prairie grass)	1	1	1	(Sithamparanathan *et al.* 1986; Hume & Barker 1991; Moloney *et al.* 1993; Scott *et al.* 1995; Stewart 1996b)
B. stamineus (grazing brome)	5	4	3	(Sithamparanathan 1979; Stewart 1996b)
B. inermis (smooth brome)	3	3	5	(Woodman *et al.* 1992; Scott *et al.* 1995)
Phalaris aquatica (phalaris)	2	3	2	(Barker *et al.* 1988; Stevens *et al.* 1988; Moloney *et al.* 1993; Oram *et al.* 2009)
Phleum pratense (timothy)	3	1	5	(Lambert 1954; Charlton *et al.* 1986; Allan & Chapman 1987; Charlton & Stewart 2000; Moot *et al.* 2000)
Legumes				
Trifolium repens (white clover)	4	3	2	(Chapman *et al.* 1985; Chapman & Fletcher 1985; MacFarlane & Bonish 1986; Chapman *et al.* 1993; Hume & Chapman 1993)
T. pratense (red clover)	2	4	4	(Musgrave 1976b; Charlton 1977; Rhodes & Clare 1983; Allan & Chapman 1987; Scott & Covacevich 1987)
T. ambiguum (Caucasian clover)	3	2	5	(Lucas *et al.* 1980; Daly & Mason 1987; Allan & Keoghan 1994; Moorhead *et al.* 1994; Pryor *et al.* 1996; Scott 1998)
T. subterraneum (subterranean clover)	4	5	1	(Charlton 1977; White & Meijer 1978; Chapman *et al.* 1986; MacFarlane *et al.* 1989; Smetham 2003b; Grigg *et al.* 2008)
Medicago sativa (lucerne)	1	1	3	(Janson & White 1971; Campbell 1974; Musgrave *et al.* 1974; Musgrave 1976a; Baars *et al.* 1982; Musgrave 1983; McGowan *et al.* 2003)
Lotus pedunculatus (lotus)	5	1	4	(Charlton & Brock 1980; Lucas *et al.* 1980; Scott & Mills 1980; Sheath 1980; Wedderburn & Lowther 1985)
L. corniculatus (birdsfoot trefoil)	1	2	4	(Chapman *et al.* 1990; Woodman *et al.* 1992; Fraser *et al.* 1994; Ayres *et al.* 2006)
Trifolium hybridum (alsike clover)	1	1	4	(White & Meijer 1978; Floate *et al.* 1985; Allan & Chapman 1987; Woodman *et al.* 1992)
Hedysarum coronarium (sulla)	3	4	1	(Watson 1982; Niezen *et al.* 2002)
Herbs				
Cichorium intybus (chicory)	2	2	1	(Korte & Rhodes 1993; Milne *et al.* 1993; Sanderson & Elwinger 2000; Li & Kemp 2005)
Plantago lanceolata (plantain)	3	2	4	(Stewart 1996a; Dodd *et al.* 2000; Sanderson & Elwinger 2000; Gillespie *et al.* 2006)

while showing a strong growth response to nutrient application (Scott & Mills 1980).

Establishment of grasses is limited by seed and seedling predation, moisture deficits and competition. There may also be interactions between new versus older germplasm and other factors relevant to establishment (e.g. drought tolerance, insect predation). Perennial ryegrass germinates rapidly and is easy to establish in comparison to many other grass species (e.g. Charlton *et al.* 1986). While cocksfoot is persistent, cocksfoot and tall fescue (*Festuca arundinacea*) are slower to establish but are more drought tolerant than perennial ryegrass (Chapman *et al.* 1985; Meurk & Turner 1985). Both cocksfoot and tall fescue are unlikely to maintain their presence in a pasture through natural self-seeding and seedling recruitment (Hume & Barker 1991). There are numerous *Bromus* species with different environmental tolerances. Of these, prairie grass has been used most widely, and is best established in spring (Sithamparanathan *et al.* 1986). Phalaris (*Phalaris aquatica*) is also drought tolerant and can spread by rhizomes but has potential production of toxic alkaloids and it may not be as well adapted to surface sowing as perennial ryegrass and cocksfoot (Campbell 1968; Stevens *et al.* 1988). Negligible literature was found on establishment of timothy (*Phleum pratense*) in hill country and given its preference for cool and moist environments it is not recommended for summer-dry hill country (Charlton & Stewart 2000).

Little information is available on the establishment of chicory (*Cichorium intybus*) and plantain in hill country. While both are drought tolerant, plantain appears to be more promising in drought prone country as it is more persistent than chicory. Both species have epigeal germination and may therefore benefit from the presence of litter.

More recently, a summer crop, sometimes sown with forage herbs and clovers, has been used during the renewal process (Lane *et al.* 2016). A summer crop provides high quality forage and an opportunity for weed control before sowing the pasture mix.

Sowing

Seed quality, of which germination percentage is a key measure, can be used to adjust sowing rates as was demonstrated in studies on white clover, subterranean clover, strawberry clover (*Trifolium fragiferum*), lotus, perennial ryegrass and cocksfoot (e.g. Charlton & Giddens 1983). Interspecific variability in seed germination, even within the same trial, emphasises the importance of routine seed testing.

Sowing date is critical; in the South Island, the best time to oversow varies from early August on low sunny faces to late September on higher shady faces (Allan *et al.* 1985). In North Island summer-dry hill country, oversowing in autumn is considerably more successful than in spring, whereas in summer-moist country, oversowing in spring is more successful than oversowing in autumn (Lambert *et al.* 1985). The likely environmental conditions for the first few months following oversowing are important when deciding sowing time. For example, germination of lotus ‘Grasslands Maku’ is low at low temperatures (e.g. 5^{o}C, Charlton 1989) and is better sown in early autumn or in mid- to late spring, when soil temperatures are higher. In contrast, red clover and white clover are less temperature dependent and their germination will generally be higher than that of lotus if sown in late autumn or early spring (Hampton *et al.* 1986). There are also differences between grass species; perennial ryegrass germination is less sensitive to temperature than that of timothy, phalaris, prairie grass (*B. wildenowii*), cocksfoot and tall fescue. Therefore perennial ryegrass is likely to have higher germination than these species in late autumn when soil temperatures are lower.

A large range of seed mixtures are sown, from single species of grass or legume, through to grass-legume mixtures comprising up to ten species. Limited research has been conducted on the establishment and ecological merits of oversowing grasses and legumes together versus oversowing legumes first and grasses later (e.g. White *et al.* 1972). If grasses are introduced later, then strategies to manage the existing vegetation comprising the new legume germplasm, are poorly defined. Sometimes, seed is sown with fertiliser but in the literature, responses depend on the existing soil fertility status, fertiliser type and rate, time of application, and species sown. Legumes often respond to increasing rates of phosphate whereas application of this nutrient mostly has negligible or no effect on grass establishment (e.g. Cullen *et al.* 1966; Lucas *et al.* 1980).

Pests consume seeds and defoliate germinating seedlings (e.g. slugs, caterpillars, field crickets, birds) and have accounted for the loss of up to 5% of the seed sown (Barker & Zhang 1988).

While many New Zealand soils now contain effective *Rhizobium* strains that can nodulate white clover, red clover and alsike clover (*Trifolium hybridum*) (Andrews *et al.* 2015), inoculation may be required on new pastoral land that has been cleared directly from scrub or pastoral land where there is no evidence of resident clover (Lowther & Kerr 2011). It is essential to inoculate seed of legumes new to an area and best to sow immediately after inoculation to minimise storage time and enhance rhizobia survival. Lime pelleting and high inoculation rates enhance establishment under favourable conditions following oversowing, but results are less satisfactory under adverse conditions such as hot, dry conditions (White 1973). Using coated grass seed can result in large increases in establishment by improving germination, possibly through altered moisture patterns, although results are highly variable (Allan *et al.* 1985).

Technology is available to apply a range of microbes to the surface of seeds that can provide control of insect pests and diseases, improve nutrient uptake, or promote growth (Bashan 1998). However, this requires more than just a microbial coating. Using a formulation science approach (McQuilken *et al.* 1998), other physical components and chemical amendments can be incorporated in successive layers around the seed. Also, there are alternatives to traditional aerial delivery of seeds, such as hydroseeding or dispersal after ingestion by sheep or cattle (Aird 2008). Protection from digestion could also be included in future seed coat design. Clever seed coats can be developed to utilise a range of properties such as insect pest control, fungal pathogen control, seedling inoculation and growth enhancement, and increased availability of nutrients, to achieve a step-change in seed establishment in challenging hill country environments.

Post-sowing management

Trampling areas immediately after oversowing with high stock densities for short durations (mostly hours) increases seed-soil contact. No literature could be found on the effectiveness of this practice on factors such as depth of seed burial. Sheep are used most often (e.g. 1 700 ewes/ha for 2-5 hours), and less frequently, cattle (e.g. Barker *et al.* 1988; Hume & Chapman 1993).

Little research has been conducted on pest control. Application of parathion reduced seedling losses of white clover and lotus from 19% to 1% eight weeks after sowing (Barratt & Johnstone 1984) and in the North Island, it was found that adult porina and grass grub were less likely to lay their eggs in short than long pasture (Suckling 1966).

Fertiliser, mainly superphosphate, was added within one year after species introduction in a few studies in the North Island but the benefits of application were uncertain within the seedling establishment period (Suckling 1950).

Regrowth of resident vegetation is a major challenge to seedling establishment (e.g. Suckling 1966). Grazing management can assist in management of this and time of first grazing after sowing will depend on location, botanical composition of the existing sward, and introduced species, e.g. grasses vs legumes. Spelling grass seedlings for 6-8 weeks may enable them to develop strong root systems before grazing (Suckling 1966). Both set stocking and rotational or intermittent grazing may be appropriate options for at least the first 12 months after sowing (e.g. Cullen 1971; Sheely & Pringle 1979). Reproductive growth of grasses during summer and autumn sometimes makes grazing difficult because of the relatively unpalatable herbage, which requires longer periods of stock grazing to achieve acceptable utilisation (Suckling 1959). It appears that no research has been conducted on the efficacy of using herbicides to control regrowth of the resident pasture after sowing.

Other techniques for establishing species

Natural reseeding of legume species was investigated in the lower North Island in the 1950s/1960s, focusing on the potential to increase quantity of buried seed (Suckling 1951; Suckling 1966). Reseeding of white clover, red clover and lotus is negligible under close continuous grazing whereas reseeding of subterranean clover can still occur (Suckling 1951). With an initial nucleus of plants of *Trifolium* spp. established from oversowing, it is possible to thicken a stand by spelling over the summer. Length of spelling for best results varies with species, ranging from 6 weeks for white clover to 3 months for red clover and lotus (Suckling 1951). There is a lack of recent research on natural reseeding of legumes in New Zealand hill country.

Reseeding in tall fescue, phalaris and cocksfoot is negligible while that of perennial ryegrass and prairie grass is greater (Hume & Barker 1991). Prairie grass presence, in particular, depends on natural reseeding. No information was available on the reseeding of herbs. Livestock may also introduce and disseminate legume seed. In one study, cow dung contained 7 788 legume seeds per kg, equivalent to 11.9 kg/ha (Suckling 1951). When ingested and passed through sheep, hard seed of white clover has a higher survival rate than non-hard seed (Suckling 1952). Grazing sheep on areas of white clover with ripe seed, or on seed crops, and then transferring them to clover-deficient hill country, could be potentially useful approaches. Another option is feeding hay with high seed content, and likely high hard seed content (Suckling 1966). Modern seed coating technologies could be used to protect ingested seed for subsequent dispersal by grazing animals.

Future research directions

Given the importance of hill country in New Zealand for agricultural production and the current environmental challenges it faces (Anon 2015), further research is required that results in economically and environmentally sustainable management practices. While much has been done, gaps remain. Based on this review, key gaps include:

- Pre-sowing management: strategies to reduce seedling desiccation during the establishment phase (including the potential for seed coating materials to increase water retention and seedling survival),

optimal herbicide application rates and weed control during establishment, the impacts of chemical fallows and litter on subsequent establishment, annual legume management to ensure reseeding, and forage herb establishment.
- Sowing management: sowing sequence strategies to enhance legume establishment, novel strategies to increase seed-soil contact (including novel seed coating / pelleting techniques), rhizobia management, pest control, strategies to improve seed dissemination (including coatings to enhance establishment success and the role of grazing livestock), and strategies that improve aerial application and a more even distribution of seed.
- Post-sowing management: efficacious herbicide use for weed control.

Continuing collaboration between research agencies, industry bodies, regional councils and innovative farmers will ensure that the most relevant research programmes on pasture establishment are conducted to provide national benefit for hill country livestock enterprises and the rural communities they support.

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