REVIEW

Potential of direct seeding for establishing native plants into pastoral land in New Zealand

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Abstract: Native plants are an important part of New Zealand's uniqueness, and there is increasing awareness of the need to maintain these species in managed landscapes, particularly pastoral areas, in addition to the country's conservation lands. The most widely used method of establishing native plants is transplanting nursery-grown seedlings, and for many species, much experience and knowledge has been gained in using this technique. Establishment of native plants in the field by direct seeding is a potentially useful alternative technique—which has been evaluated in the North and South Islands only to a limited extent. This paper reviews the current state of knowledge on the direct seeding of species into pastoral areas. It covers site and species selection, seed availability and quality, site preparation, and post-sowing management. It also compares the economics of native plant establishment by transplanting and by direct seeding. Direct seeding of pastoral areas is a relatively cheap technique, but its general applicability is currently limited because of frequently inadequate supplies of viable seed, lack of knowledge on appropriate sowing times and rates, unreliable field germination and seedling emergence, and frequent intense competition from existing vegetation, particularly exotic grasses.

Keywords: establishment; hill country; seedling competition; seed quality

Introduction

There is increasing desire amongst private landowners and agencies to introduce native plants into rural landscapes (Parliamentary Commissioner for the Environment 2001), such as those currently supporting pastoral farming. The reasons for this are numerous and varied and include increasing floristic (and often faunal) biodiversity, landscape and habitat enhancement, cultural values, long-term land stabilisation, development of premium plant products, and provision of shade and shelter for livestock.

The long-established and often most reliable method of introducing native plant species to a variety of sites has been the transplanting of glasshouse- or nursery-prepared plants (Pollock 1986; Porteous 1993). This enables significant control over the environment in which seeds germinate and seedlings grow compared with open field conditions, resulting in relatively high and more rapid germination, and higher seedling survival. However, the cost of transplanting native shrubs over large areas is expensive in the context of pastoral farming systems. The cost of establishing native shrubs at 2500 stems ha^{-1} (2×2-m spacing) can be NZ$15,000–20,000 ha^{-1}, with additional follow-up weed and pest control costs of NZ$2,000–3,000 ha^{-1} yr^{-1} for 3–5 years. More widespread planting of natives will require the development of more-cost-effective approaches.

Direct seeding of native plant species into pastoral hill and high country landscapes is a potentially useful alternative or complementary option to transplanting seedlings that is receiving increasing attention (Grant 1967; Evans 1983; Porteous 1993; Sessions & Kelly 2000; Ledgard & Davis 2004; Miller & Duncan 2004; Stevenson & Smale 2005; Dodd & Power 2007). The main advantages of direct seeding are the ability to sow large areas rapidly by hand or with broadcasting machinery, lower cost compared with transplanting seedlings, and seedlings' development of well-structured root systems. Consequently, established plants are often less prone to toppling and have unhindered taproot formation compared with container-grown seedlings, which may develop restricted, 'cork-screwed' roots and distorted taproots. This is especially so for tree species that can be established in the field from seed such as *Corynocarpus laevigatus* and *Beilschmiedia tarairi*. Furthermore, direct seeding is considered to produce a more natural appearance and successional pathway compared with spaced-planting (e.g. at 2500 stems ha^{-1}). However, direct seeding also has a number of potential disadvantages, including difficulties sourcing large quantities of viable seed, lack of information on optimum sowing times for many species, variability in commencement and duration of germination, less flexibility to control conditions for seed germination and early seedling growth, predation of seed and seedlings, and the need to control intense competition from existing vegetation, particularly grasses.

This paper reviews and highlights key factors to consider with direct seeding native species into pastoral land (Table 1) and compares the economics of establishing native plants by transplanting with those by direct seeding. The focus is on open pasture (areas devoid of trees or forest), which avoids the more complex biological interactions that occur adjacent to and within forest remnants. However, many of the principles and issues, for example seed quality and weed control, are applicable to these situations and vice versa. There are few published results from field trials in open pasture in New Zealand, but other literature dealing with direct seeding or oversowing in general is cited where appropriate. International experience with direct seeding of native species and related issues is considerable, for example in the UK (Pywell et al. 2003; Smith et al. 2003), North America (Buisson et al. 2006; Burton et al. 2006), and Australia (Knight et al. 1998; Standish et al. 2007), and many of the principles developed internationally have relevance in New Zealand.

Site and species selection

Areas considered for introduction of native species, including by direct seeding, should be those where there is the greatest chance of successful seedling establishment and growth, and potential sites should be characterised with respect to key attributes likely to affect plant establishment, growth and survival (Porteous 1993). Environmental tolerances and suitabilities of 80 native plant species comprising herbs, shrubs and trees were compiled by Pollock (1986). This database was expanded to 320 species of practical

Table 1. Issues to consider in the direct seeding of New Zealand native plant species into pastoral areas and the level of knowledge and experience available.

Issue	Knowledge or experience available	Selected references
1) Site and species selection	High	Pollock 1986; Wardle 1991; Porteous 1993
2) Seed		
– availability: quantity, collection time	Low/Moderate	Evans 1983; Porteus 1993
– viability and germination	Low/Moderate	Evans 1983; Fountain & Outred 1991; Porteous 1993; Hill 2004
– dormancy breaking	Low	Evans 1983; Porteous 1993; Mackay et al. 2002
3) Site preparation		
– fencing to exclude domestic livestock and feral animals	High	Evans 1983; Porteous 1993; Stevenson & Smale 2005
– suppression of existing pasture	High	Evans 1983; Porteous 1993; Stevenson & Smale 2005; Dodd & Power 2007
– substrate preparation and benefits for species	Low	Stevenson & Smale 2005; Dodd & Power 2007
4) Sowing		
– rates	Low	Ledgard & Davis 2004; Stevenson & Smale 2005; Dodd & Power 2007
– timing, e.g. autumn vs spring	Low	Dodd & Power 2007
– single species vs mixtures	Low	Ledgard & Davis 2004; Stevenson & Smale 2005
– method	High	Evans 1983; Porteous 1993; Dodd & Power 2007
– seed coatings	Low	None found
5) Post-sowing management		
– control of regrowth of existing vegetation and weeds	Low	None found
– pest control	High	Evans 1983; Porteus 1993

value in restoration projects as part of the development of a decision support system, The Green Toolbox (www.landcareresearch.co.nz/research/biodiversity/greentoolbox/), prepared by Landcare Research and other agencies in the 1990s.

Many lists of vascular plant species in different locations and environments were used by Rogers and Walker (2005) in their study on aspects of the evolution of the New Zealand vascular flora. Studies have been conducted to obtain a greater understanding of the environmental factors influencing the distribution of the country's flora, and some of these relationships have been modelled (Leathwick et al. 1996). There is good knowledge of appropriate sites for a number of native species that may be introduced into localities within particular ecological zones.

Intraspecific genetic variation for numerous attributes has been documented for some horticulturally important species, such as *Cordyline australis* (Harris et al. 2003), *Hebe* spp. (Kellow et al. 2005), and *Phormium* spp. (Harris et al. 2005), supporting the recommendation of using locally sourced seed for restoration projects (Pollock 1986; Porteous 1993); local seed produces plants which are better adapted to local conditions (McKay et al. 2005). A corollary is that using locally sourced seed will minimise the risk of altering natural genetic variation in a species.

For direct seeding, species could be selected according to the following criteria: (1) locally native; (2) adaptation to open, low/moderate-fertility environments; (3) tolerance of browsing, e.g. by rabbits and hares; (4) growth form, e.g. height >500 mm to compete with herbaceous exotic species; (5) biological status of substrate, e.g. mycorrhizae; and (6) rate of seedling establishment, particularly time from sowing to germination and seedling growth rate within the first 6–12 months. In pastoral situations, seedlings of native species are usually exposed to intense competition from resident pasture, so that quick establishment is of paramount importance. Hence species with short times to germination and fast early growth rates (e.g. *Hebe stricta*, *Kunzea ericoides* and *Leptospermum scoparium*) are favoured. It needs to be recognised that some species selected for early establishment success may not be long-lived and a deliberate replacement strategy such as interplanting may need to be implemented.

Seed availability and quality

It is imperative that seed of selected native species be available in sufficient quantities to meet requirements and at reasonable cost. Hampton and Hill (2002) highlighted the inconsistency in annual seed production and the lack of knowledge of optimum seed collection times, and processing and storage protocols, for many native species. Species selection and seed collection are critical steps in the restoration process, and because seed availability can be limiting, it needs to be considered long before the actual time of sowing. In most instances, seed is collected by hand from appropriate plants—a slow process that limits the quantities of viable seed available for large-scale restoration programmes. Seed of *Leptospermum scoparium* has also been collected by mulching branches laden with seed and storing in wool bales, which is much more cost-effective than collecting by hand and the advantage is also immediate bulking of the fine seed (R. Simcock, Landcare Research, Auckland, NZ, pers. comm.). Harvested shoots and seed capsules have also been used successfully to establish native species overseas (e.g. Pywell et al. 1995).

There are comprehensive long-term datasets on seed yield for a number of New Zealand native species, particularly those adapted to subalpine climates such as members of the genera *Chionochloa* (Kelly et al. 2000; Schauber et al. 2002) and *Nothofagus* (Burrows & Allen 1991; Schauber et al. 2002; Richardson et al. 2005). Seed yield data (seed number per square metre, seed number per tree, individual seed weight) collected over shorter time frames are available for various tree and shrub species of a range of genera (e.g. review by Wardle 1991). Seed yield can be estimated from yield components. For example, Grant (1967) determined that a 10-year-old plant of *Leptospermum scoparium* had 8000 capsules in the autumn-winter period, with an average of 300 (range 240–470) seeds per capsule. This equated to 2.4 million seeds, and assuming a thousand seed weight (TSW) of 0.5 g (2000 seeds g^{-1}) (Hampton & Hill 2002), the plant produced 1.2 kg of seed.

Seed used in direct seeding operations, as for seed used to produce seedlings in nurseries, should be tested for viability (alive or dead) and germination characteristics to ensure that adequate seedling densities can be obtained under favourable environmental conditions. Germination levels or rates for a number of native species have been determined in controlled environments (constant laboratory conditions and/or glasshouse studies) over the last three decades (e.g. Scott 1975; Simpson 1976; Mohan et al. 1984; Court & Mitchell 1988; Fountain et al. 1989; Bannister & Bridgman 1991; Burrows 1994, 1995a,b,c, 1996a,b,c, 1999a,b; Moore et al. 1994; Bannister et al. 1996; Herron et al. 2000a,b; McGill et al. 2000; Grüner & Heenan 2001; Fountain et al. 2002; Mackay et al. 2002; Martin & Ogden 2002; Norton et al. 2002; Schmidt-Adam et al. 2002). However, this information should generally not negate the need for routine germination testing of seed batches for direct seeding projects because of variation in attributes such as source of seed, maturation conditions, physiological state, and seed size or age.

Seeds of New Zealand native species are regarded as inherently poor germinators (Fountain & Outred 1991; Bannister & Jameson 1994; Hampton & Hill

2002; Mackay et al. 2002). Although low viability may be responsible for this, there is increasing recent evidence that low germination in a range of native species may be because of seed dormancy (Hampton & Hill 2002; Mackay et al. 2002), i.e. the failure of a viable seed to germinate despite being exposed to favourable environmental conditions. Dormancy may result from physical mechanisms such as seed still being contained in fleshy fruit and seed coat impermeability, and/or physiological mechanisms such as embryo dormancy and chemical inhibitors in the seed. Dormancy and other aspects of germination of a number of native species have been reviewed recently (Fountain & Outred 1991; Bannister & Jameson 1994) and future seed research is unlikely to reveal new mechanisms of dormancy or new patterns of behaviour.

There are various techniques for breaking seed dormancy in native species (Bannister & Bridgman 1991; Fountain & Outred 1991; Bannister & Jameson 1994; Hill 2004), including stratification (chilling) for a period, exposure to light, scarification (cutting or chipping the seed coat), and chemical treatment (e.g. concentrated sulphuric acid, gibberellic acid, smoke). In a recent study, final germination of *Phormium tenax* (96% viability, 8% germination) increased to 57%, 81% and 95% following stratification at 5°C for 4, 8 and 12 weeks, respectively (Mackay et al. 2002), and germination of *Leptospermum scoparium* (unknown viability) after 23 days at 20°C was 100% under continuous fluorescent light compared with 3% in the dark. Seeds of *Sophora* spp. must be scarified to achieve high or complete germination (Stilinović & Grbić 1988; Mackay et al. 2002; Norton et al. 2002), but light is unnecessary for germination of *S. prostrata* (Mackay et al. 2002). Puncturing the testa of seed of three *Carmichaelia* spp. stored for 4 to 19 years resulted in rapid germination of greater than 90% whereas germination of unscarified seed was 0–11% (Grüner & Heenan 2001). Germination of over 80% has been achieved for seed of the native scrubweed *Discaria toumatou* by immersion in 98% sulphuric acid followed by imbibition with a solution of gibberellic acid (Keogh & Bannister 1992). The value of techniques for breaking dormancy can only be assessed fairly when the viability of the seed lot(s) is known (Hampton & Hill 2002). Breaking seed dormancy is very species specific and several methods may be needed for rapid seed germination of different species in seed mixtures. In practice, for any species, breaking seed dormancy may not be worth addressing unless a large percentage of seed is affected and the seed is in short supply (Pollock 1986).

Site preparation

Paramount to the success of any direct seeding operation is thorough preparation of the site. In pastoral situations, competition from the existing vegetation (mostly or exclusively herbaceous exotic species) is probably the greatest limitation to satisfactory establishment of sown native species (Evans 1983; Porteous 1993), and hence it needs to be controlled effectively. In the general guidelines by Porteous (1993), methods of site preparation listed, with weed control as a primary objective, were application of herbicide, screefing (removal of the surface vegetation with a spade or grubber to expose the soil; also called scalping), rotary-hoeing, ripping, discing or ploughing. On moderate to steep hill country, access to machinery and its safe operation may limit the applicability of some of these methods.

Managing existing vegetation

A range of herbicides are available to kill or suppress existing vegetation in standard pasture renewal programmes (AgriMedia 2005), and there seems no reason to doubt their suitability for preparing existing pasture sites for direct seeding with native species. The effect of herbicides on recently emerged seedlings of New Zealand native species is largely unknown, and therefore recommendations on the pre-sowing use of herbicides with residual activity, in particular, should be strictly adhered to. Limited information exists on the effect of several herbicides on more mature plants of native species (e.g. Champion 1998; Harrington et al. 1998), and where herbicides have some residual activity, this information might indicate their possible effect on very young seedlings.

Topsoil removal

The benefit of removing topsoil to a depth of 10 cm on the establishment of some native plant species was shown on pastoral hill country near Hamilton (Stevenson & Smale 2005). After one year, mean seedling density of *Kunzea ericoides* and *Coprosma robusta* was 6 seedlings m^{-2} and 6.6 seedlings m^{-2} respectively, which was significantly higher than establishment in herbicide (two successive applications of glyphosate 2% solution) and turf screefing (grass cover removed with topsoil left intact) treatments. Sown seed of *Dacrycarpus dacrydioides*, *Weinmannia racemosa*, and *Podocarpus totara* produced few or no seedlings in any treatment, indicating the considerable variability that can exist between species in establishment under the same environmental conditions. In practice, topsoil would likely only be removed from parts of a treated block on extensive pastoral hill country. Where topsoil is removed or flipped, and retained on the same treated block, it has the advantage of creating alternate double-depths of topsoil or no topsoil, and a wide range of microsites for seed germination and seedling establishment.

Soils under pastoral grazing are subject to compaction from the hoof action of farmed livestock (Betteridge et al. 1999; Greenwood & McKenzie 2001), which can seriously limit plant establishment, growth and persistence. One of the few studies on the effect of soil compaction on the establishment and early growth of New Zealand native plants found that seedling emergence of *Leptospermum scoparium* was higher in compacted (63% and 76%) than uncompacted soil (52%), and more seedlings of *Cordyline australis* penetrated the soil surface in uncompacted (96%) than compacted (27% and 50%) soil (Bassett et al. 2005). *Cordyline australis* has thicker roots than *Leptospermum scoparium*, which may partly explain their different responses in compacted and uncompacted soils.

Soil fertility

The effect of soil nutrient status on field establishment and growth of New Zealand native plants has received little attention. In general guidelines on restoration, Evans (1983) and Porteus (1993) stated that on fertile soils, many native plants grow well without the addition of fertiliser, and even on 'hard' sites, growth can be satisfactory in the absence of fertiliser. Most of New Zealand's soils have been classified as 'semi-fertile' or 'infertile' (Wardle 1991), which is probably why many native species grow well on numerous sites without additional nutrients. On bare ground (Olsen P of 10 mg kg^{-1} soil) with topsoil (0–10 cm depth) removed (Stevenson & Smale 2005), seedling establishment of *Coprosma robusta* and *Kunzea ericoides* was significantly higher than in herbicided and screefed plots that had higher soil fertility (Olsen P at least 26 mg kg^{-1} soil). Furthermore, the removal of topsoil resulted in greater bare ground after one year, and less competition for the developing native plant seedlings. The authors concluded that increasing soil fertility (e.g. by topdressing) was not advisable. This study did not separate effects of soil fertility from competition, and future experimentation should aim to determine the effect of fertility unconfounded with competition effects.

The ability of *Leptospermum scoparium* to colonise inhospitable sites, especially those of low fertility, is well documented (Grant 1967; Evans 1983; Porteous 1993; Ledgard & Davis 2004). Within two months of sowing the species on bare ground, unfertilised plots had 50 seedlings m^{-2} (Grant 1967). This was greater than densities in plots receiving 'low' and 'high' rates of applied fertiliser, which had 25 seedlings m^{-2} and 10 seedlings m^{-2}, respectively (Grant, 1967). In the same study, *Leptospermum scoparium* sown into plots of *Agrostis capillaris* cut at various frequencies attained seedling densities of up to 150 seedlings m^{-2}, compared with fewer than 50 seedlings m^{-2} in fertilised plots. In a mixed-species sowing on Canterbury foothills following a forest fire, addition of molybdenised superphosphate (1 t ha^{-1}) and di-ammonium phosphate (80 kg ha^{-1}) increased plant numbers of *Leptospermum scoparium* in the first year (37 seedlings m^{-2} vs 18 seedlings m^{-2} in unfertilised plots), but had no effect during the remainder of the 19-year trial (Ledgard & Davis 2004). Fertiliser addition had no beneficial effects on establishment of other native species.

Current knowledge and experience suggests that, in many situations, there is negligible advantage in fertilising soils to increase native plant establishment, survival, and growth. Furthermore, fertiliser additions are generally more beneficial to growth of surrounding exotic vegetation, thereby increasing the level of competition to which native seedlings are exposed. This will incur increased costs in controlling weed ingress. Most pasture sites will be of sufficiently high fertility already (Sparling & Schipper 2004).

Ectomycorrhizae and endomycorrhizae (vesicular arbuscular) fungi infect some native plant species, which may improve their phosphorus uptake (Baylis 1971; Hall 1977) and hasten growth. Species of the genera *Kunzea*, *Leptospermum*, and *Nothofagus* can form ectomycorrhizal associations in the field, and endomychorrizal infection has been reported in a number of genera and species, including *Coprosma*, *Griselinia*, *Leptospermum*, *Podocarpus*, *Metrosideros umbellata*, and *Weinmannia racemosa* (Baylis 1967; Hall 1977; Orlovich & Cairney 2004; Stephens et al. 2005). In pastoral areas, seedlings of these species established from field sowing are likely to become infected naturally by mycorrhizae within a few weeks of emergence, with consequent benefits for phosphate uptake.

Protection

Areas to be sown should be fenced to exclude domestic livestock and feral animals, as young and establishing native plants can be damaged severely (Porteous 1993). A programme involving trapping, shooting or poisoning is recommended for feral animals unable to be controlled with suitable fencing.

In the few recent field sowings reported (Ledgard & Davis 2004; Miller & Duncan 2004; Stevenson & Smale 2005), seedling mortality occurred, but it was uncertain if this was because of competition with other vegetation, aspects of the physical environment (e.g. drought, frost), or from herbivory by insects, molluscs or small animals, or a combination of these factors. In Canterbury, a trial was fenced to exclude deer (Ledgard & Davis 2004), which was perhaps the main potential pest of the sown native species. Some early mortality of *Coprosma robusta* was possibly caused by rabbit browsing in a Waikato trial where livestock were excluded (Stevenson & Smale 2005).

Sowing

Methods

Seed may be applied using routine methods for pasture establishment on hill country (Hampton et al. 1999), that is, broadcasting by hand (with bulking material such as pumice or sand to facilitate handling and spreading of small seed) or portable spreader, or by aeroplane or helicopter. However, the likely shortage of seed of many native species often precludes aerial application.

An additional option with some native species is fascining, i.e. the laying of branches with ripe seed on the prepared ground. This works well for *Leptospermum scoparium* and *Kunzea ericoides* where the technique improves the environment (shelter, increased humidity, warmth) in which the seed germinates and seedlings develop (Evans 1983; Porteous 1993). Seed of native species has also been used in hydroseeding operations, involving the application of a watery mixture of seeds, fertilisers, mulches, adhesives and other additives (Lambrechtsen 1986; Simcock & Ross 1997). The technique is used successfully on steep sites such as road and rail batters, and expensive landscaping projects, but its relatively high cost largely precludes it as a viable option for introducing native species into pastoral lands.

Maximising seed-to-soil contact when broadcasting pasture mixes can be achieved by roughening the soil surface by hard grazing with livestock before sowing, and by treading the seed in with mob-stocked sheep after sowing, as practised in hill-country pasture renewal where mechanical sowing is not practicable (Sithamparanathan et al. 1986; Hampton et al. 1999). Treading was used in the spring sowing of a mixture comprising early-colonising species (*Coprosma robusta*, *Cordyline australis*, *Dacrycarpus dacrydioides*, *Hebe stricta*, *Kunzea ericoides*, *Leptospermum scoparium*, and *Pittosporum tenuifolium*) on hill country in Waikato (Dodd & Power 2007) and resulted in seedling numbers of *Coprosma robusta*, *Cordyline australis*, *Dacrycarpus dacrydioides* and *Hebe stricta* being 3–20 times higher than in untreaded plots. However, treading was not advantageous in an autumn sowing at the same site, perhaps because soil water content (w/w; 70–90%) was higher than in spring (50–70%) and sufficient for surface or buried seed to germinate similarly and produce seedlings. Optimum sowing depth for native species remains to be determined.

Mixtures

Seed of native species has been sown in mixtures comprising six species in Canterbury (Ledgard & Davis 2004), six species in Waikato (Stevenson & Smale 2005), and seven species in Waikato (Dodd & Power 2007), with varying levels of establishment success. Species that established relatively well in these trials and their TSWs (calculated from presented data, where required) were *Leptospermum scoparium* (TSW = 0.01 g) and *Nothofagus solandri* var. *cliffortioides* (4.5 g) (Ledgard & Davis 2004); *Coprosma robusta* (8.3 g) and *Kunzea ericoides* (0.02 g) (Stevenson & Smale 2005); and *Coprosma robusta* (6.6 g) and *Hebe stricta* (0.08 g) (Dodd & Power 2007). These species are all recognised as pioneer or early colonising species (Pollock 1986; Porteus 1993), except for *Nothofagus solandri*, which is classified as a successional species (Pollock 1986). A feature of three of the species (*Hebe stricta*, *Kunzea ericoides* and *Leptospermum scoparium*) is their very small seed with a TSW of <0.1 g. In hydroseeding mixtures applied to road batters, native species establishing successfully have included *Coprosma robusta*, *Coriaria arborea*, *Hebe stricta*, *Leptospermum scoparium*, and *Phormium tenax* (R. Simcock, pers. comm.), which partly mimics experience in pastoral situations (Stevenson & Smale 2005; Dodd & Power 2007).

The findings from these studies suggest one or more species that could be included in mixtures for general restoration work. However, there is insufficient research information available to promote widespread sowing of mixtures of native species; appropriate companion species and their relative proportions in a mixture need to be determined for particular sites.

Rates

Direct seeding of native species has not been developed to the stage where field sowing rates can be recommended. In the negligible field research conducted, rates used have been based on the quantities of seed available (Ledgard & Davis 2004; Stevenson & Smale 2005; Dodd & Power 2007) or on those required for the experimental design (Miller & Duncan 2004). In Canterbury, Ledgard and Davis (2004) sowed a seven-species mixture with components ranging from 0.1 kg ha^{-1} (2.3 seeds m^{-2}) for *Coprosma* spp. to 6.0 kg ha^{-1} (6000 seeds m^{-2}) for *Leptospermum scoparium*, and Stevenson and Smale (2005) in Waikato pastoral land sowed a six-species mixture with rates ranging from 1.8 kg ha^{-1} (4000 seeds m^{-2}) for *Weinmannia racemosa* to 10.0 kg ha^{-1} (45 seeds m^{-2}) for *Dacrycarpus dacrydioides*. Also in Waikato, Dodd and Power (2007) sowed a seven-species mixture in spring with components varying from 118 seeds m^{-2} for *Coprosma robusta* to 5188 seeds m^{-2} for *Leptospermum scoparium*. In a trial the following autumn, they sowed the mixture at 0.25-, 0.5-, 1-, 2- and 4-times that used in spring and found that seedling numbers of *Coprosma robusta* and *Hebe stricta* increased linearly with sowing rate. The number of seedlings of the other species was insufficient to determine relationships between seedling number and sowing rate. At several sites in the lower South

Island, seed of *Pachycladon cheesemanii* was sown at about 5560 seeds m^{-2} (500 seeds in plots of 30 × 30 cm) or 8890 seeds m^{-2} (800 seeds per plot) (Miller & Duncan 2004).

Broadcasting exotic pasture species often results in only 5–20% of sown seed producing established plants (Hampton et al. 1999), and it is possible that a similarly low result will be achieved with many native species. Support for this was found in Waikato where the number of plants established 2.5 years after autumn sowing, as a percentage of seed sown, was <1% for *Hebe stricta* and about 2% for *Coprosma robusta* (Dodd & Power 2007).

There is large variation in TSW of New Zealand native plants (Hampton & Hill 2002). For example, species with very small seed are *Hebe stricta* with a TSW of 0.05 g (20 000 seeds g^{-1}) and *Leptospermum scoparium* with a TSW of 0.5 g (2000 seeds g^{-1}). Much larger seeds are produced by *Corokia macrocarpa* (TSW = 66.6 g; 15 seeds g^{-1}) and *Myoporum laetum* (TSW = 58.8 g; 17 seeds g^{-1}). In deciding sowing rates, seed weight information needs to be considered together with target plant populations, seed quality, and likely seedling emergence and survival. Seed availability (and cost) may override other factors in final sowing rates used, such as occurred in Canterbury (Ledgard & Davis 2004) and Waikato (Stevenson & Smale 2005).

Timing

The best time to sow most native plant species in the field is unknown, but will depend on seed characteristics such as freshness, viability and germination, and environmental conditions at the site, particularly current and post-sowing soil temperature and soil water content, and biological features such as weed population dynamics.

In South Island trials, a seed mixture of native species including *Aristotelia serrata*, *Griselinia littoralis*, *Leptospermum scoparium*, and *Nothofagus solandri* was sown in Canterbury in September, but only the latter two species established satisfactorily (Ledgard & Davis 2004). In Canterbury and Otago, seeds of *Pachycladon cheesemanii* were sown at one site in November and at other sites in January, and seedlings emerged in some treatments at each site (Miller & Duncan 2004). In both studies, the native seeds were not tested for viability or germination before sowing, so that reasons for any establishment failures (and successes) were not always clear.

In hill country in Waikato, North Island, a seven-species mixture was broadcast-sown in spring and autumn at a range of rates and with and without mob-stocking by sheep (Dodd & Power 2007). Over half the species emerged in each season, with *Coprosma robusta* and *Hebe stricta* being the most successful and some plants surviving throughout each trial, conducted for 2.5 or 3 years. Relatively high soil water content at sowing in autumn and its maintenance for a longer period after sowing than in spring were considered beneficial for establishment. The decreasing soil temperatures during autumn were unlikely to be a severe limitation to seedling establishment at the relatively temperate site.

Post-sowing management

Assuming that livestock and pests are controlled effectively, the major challenge to address following sowing is weed competition, particularly from exotic grasses. Growth of weeds must be suppressed to reduce competition for the emerging seedlings. The necessity for weed control has been recognised for many years where native plants have been established using transplanted nursery seedlings, and a number of options are available (Evans 1983; Porteous 1993). In the direct seeding situation, weed control is probably limited mainly to application of appropriate herbicides, although hand-weeding may be considered where sowing has been conducted in sprayed spots (e.g. <1 m in diameter) rather than the more usual spraying of all vegetation in an area. The removal of topsoil before sowing (Stevenson & Smale 2005) may reduce weed control requirements, but it is not practical in pastoral situations. Nevertheless, techniques such as grazing, which disturb and reduce existing vegetation, may go some way to reducing subsequent weed ingress and their effectiveness needs to be quantified.

Economics

Revegetation costs using nursery-prepared native plants range from NZ$17,000 to $25,000 per hectare (Taylor 2005). A comparison between native plant establishment using spaced plants and direct seeding is presented in Table 2. In each option there is large variation in total cost, depending mainly on the plant size or species used. However, the comparison shows that to attain 2500 plants ha^{-1}, direct seeding is generally the cheapest option. Only further experimentation will determine if the costs for direct seeding, in particular, are appropriate. One of the largest uncertainties in the calculations for direct seeding is the assumption that seedling survival is 20%, because this will depend considerably on the effectiveness of managing the post-sowing ingression of existing pasture and broadleaved weeds.

The costs in Table 2 are mostly at contract and/or retail rates, and some costs could be reduced if the landowners conducted some of the work themselves. Also, fencing costs could be reduced significantly by partly using existing fences; for example, establishing

Table 2. Comparison of estimated costs (NZ$ ha^{-1}) for spaced planting and direct seeding of New Zealand native species on pastoral land.

Item	Spaced planting[1]	Direct seeding
Fencing [2]	4320–4770	4320–4770
Pest control [3]	10–15	10–15
Pre-plant/pre-sow herbicide		
Spot spraying [4]	750	
Blanket spraying [5]		150–165
Planting [6]	2125–3000	
Sowing [7]		70
Plant cost [8]	3000–11 250	
Seed cost [9, 10]		75–8000
Transportation [11]	1500	20
Post-plant/post-sow herbicide [12]		
Y1	750	90–420
Y2	750	90–420
Y3	750	90–420
TOTAL	13 955–23 535	4915–14 300

Assumptions: [1] 2500 plants ha^{-1} (2 × 2 m); [2] seven-wire batten fence and 1 ha being 100 × 100 m (based on data from Burtt (2004)) – electric fencing would be less permanent, but cheaper; [3] rabbits and possums; [4] 30c per plant; [5] glyphosate at 4L of product per hectare + application costs; [6] $1.20–$4.50 per plant; [7] motorbike + spreader + ‘bulker’ for small seed quantities; [8] $0.85–$1.20 per plant; [9] seed of *Hebe stricta* (TSW = 0.05 g) @ 12.5 g ha^{-1} = $75, seed of *Sophora tetraptera* (TSW = 50 g) @ 12.5 kg ha^{-1} = $8,000; [10] 5% seedling emergence and 20% seedling survival to give 2500 plants ha^{-1} requires sowing of 250 000 seeds ha^{-1}; [11] 60c per plant and courier charge for seed; [12] 30c per plant and two blanket sprayings of seedlings applying glyphosate at 0.8 L of product per hectare ($90–$120) or haloxyfop at 2 L of product per hectare ($390–$420).

1 ha of native plants in the corner of a paddock would mean that two sides of the square (or rectangle) area would be fenced already.

Conclusions

Direct seeding of native species into pastoral areas may be a practical option and cheaper than spaced planting, but there are several aspects that need to be addressed before the technique can be used more widely. Key aspects are seed availability and quality, appropriate mixtures and sowing rates, and control of existing vegetation pre- and post-sowing. There is currently little knowledge and experience in these areas. There has been an emphasis on seed biology of native species under laboratory conditions but negligible direct seeding research. It is hoped that this imbalance will be addressed within the next few years. Direct seeding will invariably be compared with the use of transplants with respect to practicality, cost, and reliability.

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