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REVIEW **Open Access**

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Use of nitrogen-fixing plants to improve planted forest soil fertility and productivity in New Zealand: A review#

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Abstract

Background: Planted forests with low fertility soils are likely to require increased inputs of nitrogen (N) to satisfy increasing productivity demands. The use of N fertilisers will become more challenging due to their increasing cost and the risk of unwanted environmental impacts. Nitrogen-fixing plants may provide an alternative option to chemical fertilisers that is not only cheaper but has a lower greenhouse gas footprint.

Methods: Information on N-fixing plants was collated from available literature, focusing on species previously associated with planted forests as well as other exotic N-fixing trees and New Zealand native plants not used in commercial planted forests.

Results: Benefits to planted forest growth in New Zealand by N-fixing plants have been proven in only a few cases. *Lupinus arboreus* Sims was used in the 1970s and 1980s to increase N inputs in a planted *Pinus radiata* D.Don coastal forest, and improved *P. radiata* productivity was demonstrated. Productivity gains ceased when a blight disease infected the lupin population. Many N-fixing plants have been shown to tolerate low fertility soils and establish in planted forests, but there is limited information on their N contribution to the soil, and whether this N contribution increases *P. radiata* productivity. Such N-fixing plants include *Lotus* species, clover (*Trifolium* species) and weeds such as gorse (*Ulex europaeus* L.) and broom (*Cytisus scoparius* (L.) Link), which are commonly found in association with *P. radiata* forests. New Zealand native N-fixing shrubs may be suitable but there is limited information available describing N-fixation or forestry management for native plant species.

Conclusions: Nitrogen-fixing plants are a valuable resource, which when managed properly could be used for enhancing productivity. Issues with pests and disease, and limited knowledge regarding the management of N-fixing species, restricts adoption in planted forests. Well-designed research is needed to assess impacts on whole forest system N cycling as well as selection of appropriate plant species for use in planted forests without unintended consequences such as competition for soil moisture or light. This research needs to be integrated with forest management and delivered as practical options to ensure success.

Keywords: actinorhizal; forest management; kowhai; legumes; mixed species; nitrogen-fixation; native forestry; nitrogen-fertiliser; nutrient deficiency; radiata pine

 # This paper is dedicated to Dr Ruth Gadgil (1936 – 2023) for her major contributions to research on nitrogen fixation, the nutritional requirements of radiata pine, and other forest research during her long career at the New Zealand Forest Research Institute/Scion.

Introduction

Forestry is increasingly considered an option to mitigate the impacts of climate change and is a key part of New Zealand's strategy to meet its climate change obligations. As well as sequestering carbon, biomass from forestry is expected to play an important role in the transition from a fossil fuel to a biobased economy (New Zealand Productivity Commission 2018). Harvest volumes are expected to increase to meet the biomass demand for timber, bioenergy and fibre products. This will require increased productivity as more wood is produced from a finite land area (Clinton 2018).

The long-term productivity of planted forests depends upon the maintenance of soil fertility. Planted forests are supported by soils with a wide range of natural fertility due to variation in soil types and legacy effects from previous land uses (e.g., fertiliser use for pastoral grazing) (Watt et al. 2008; Ross et al. 2009; Beets et al. 2019; Garrett et al. 2022). One third of planted forests in New Zealand are on soils that are nutrient deficient (Garrett et al. 2015). Nitrogen (N) is typically the key nutrient limiting forest productivity in New Zealand and N inputs will need to increase in low fertility soils to satisfy productivity demands (Clinton 2018; Beets et al. 2019).

In New Zealand, *Pinus radiata* D.Don is a medium density soft wood (Cown 1992) and is the dominant species in planted forests due to its fast growth rate (O'Loughlin 2005), valuable wood properties (Bayne 2015) and its pulp quality (Uprichard 1980). Some 90% of the trees in New Zealand planted forests are *P. radiata* (New Zealand Forest Owners Association 2023). By international standards, the rotation length of planted forests in New Zealand (e.g., ca. 28 years for *P. radiata* (New Zealand Forest Owners Association 2023) is short and the forests are recognised as being very productive (Clinton 2018).

Nitrogenous fertiliser applications increase *P. radiata* productivity in low fertility soils (Mead & Gadgil 1978; Mead et al. 1984; Hunter et al. 1986; West et al. 1988). However, the mean annual rate of N fertiliser use across the New Zealand planted estate is 8 kg ha^{-1}, which is low compared to other sectors (Matson 2019). The main limitation on fertiliser use has been uncertainty around return on investment (Smaill & Clinton 2016). More recent research and associated models have been developed to increase confidence in the N fertiliser response in low fertility forest soils in New Zealand (Smaill et al. 2011; Garrett et al. 2021). However, N (urea) fertiliser prices show an inexorable increasing trend over time; from US$42.25 per metric ton in 1960 to US$411.38 in October 2023 with major fluctuations (lowest price US$16 in 1971, highest price US$925 in April 2022) (World Bank 2023) driven by fossil fuel supplies and prices (Snapp et al. 2023). Increased use of N fertiliser is likely to be limited by escalating fertiliser costs, challenges to sustainable fertiliser manufacture (Razon 2018; Galloway et al. 2021; Ghavam et al. 2021) and environmental regulations and societal values (D. Hall 2019; Ministry for the Environment 2020).

An alternative to manufactured N fertiliser is the use of N-fixing plants to increase soil fertility and forest productivity. Biologically fixed N is a renewable resource, in contrast to the large amounts of energy required to manufacture N fertiliser (Razon 2018), and could be a more economically attractive, environmentally sustainable and socially acceptable approach to supplying N (Jensen & Hauggaard-Nielsen 2003). Biological N fixation is the process by which atmospheric N is converted to plant-available ammonia by symbiotic or free-living bacteria. The fixed N is supplied to the host plant in inorganic forms, supporting biomass production. There are multiple pathways through which fixed N is transferred to non N-fixing plants, including indirect transfer through decaying biomass and direct transfer through below ground root exudates and shared fungal networks (Richards et al. 2010).

Nitrogen-fixing plants were employed in New Zealand planted forests to improve soil fertility and crop productivity on sand dune plantations in the 1970s and 1980s (Gadgil 1971, 1983; Beets & Madgwick 1988). However, issues with diseases and pests, identified during this era, prevented adoption at scale across the forestry estate (Dick 1994). Other factors preventing adoption include limited knowledge regarding the management of N-fixing species in the planted forest environment, concerns about competition with the tree crop, and, as with fertiliser use, a lack of confidence on return of investment (Turvey & Smethurst 1983a).

In the New Zealand agricultural sector, N-fixing plants have been the focus of much research including, but not limited to, physiology and growth, management, cultivar development and resistance to pests and diseases (reviewed by Caradus et al. 1995). The use of clovers as the main source of N declined in the 1990s following a shift to N fertiliser in the 1990s, but N-fixing plants are still very important in marginal pastoral agriculture (Moot 2012; Nichols et al. 2016).

Increased emphasis on sustainability goals, including the use of renewable resources, is drawing attention to the use of alternative management options to increase soil fertility and improve productivity to meet the global growing demand for wood (Clinton 2018). Nitrogen-fixing plants have the potential to increase soil N (Waring & Snowdon 1985) and offer new pathways to amend N deficient soils while potentially providing other ecosystem services such as increased resistance to soil erosion (Phillips et al. 2015). The use of N fixation in planted forests has received little attention in recent years, but given the increasing cost and environmental impact of N fertiliser production, it is timely to re-visit previous research on this topic.

This review consolidates the available literature on use of N-fixing plants in New Zealand planted forests. Our objectives were to examine and synthesise research on N-fixing plants that have previously been identified as having potential for this purpose as well as exotic and native N-fixing plant and tree options that have not been explored in New Zealand planted forests. We also provide insights on research required for the application of N-fixing plants to increase planted forest productivity.

Methods

Information on N-fixing plants suitable for New Zealand planted forests was obtained through a literature search in peer-reviewed journals and books using the Scopus and Google Scholar platforms. In addition, the Scion data base and National Forestry library catalogue were examined to ensure all relevant items were captured. The following search terms were used; nitrogen fixing plants, legume, rhizobia, actinorhizal, forestry, radiata, and agriculture. The last search was conducted on 14/11/2023. The publications retrieved in the search were screened to primarily identify studies with N-fixing plants and trees already present in New Zealand (in forests or agriculture). Once potentially suitable N-fixing species were identified, further searches were conducted using the N-fixing species common and scientific species names as the search term. Also included were studies of N-fixing plants and trees from regions in Australia where climatic conditions are similar to New Zealand's (i.e., ranges in mean annual temperature from 10 to 16 °C, mean annual rainfall from 600 to 1600 mm yr^{-1}) and seasonal climatic conditions that can result in frosts and long dry periods. We excluded studies from tropical forest systems. Many legume crops such as peas, lentils, chickpeas, faba beans, soybeans and *Phaseolus* beans, have not been grown in planted forests and were not considered in this review. Agroforestry was outside the scope of this review; however, some New Zealand agroforestry studies, where livestock grazing had not occurred, were included. Invasive weeds such as gorse and broom were included in the review due to their existing presence in many New Zealand planted forests. Relevant information obtained from the literature review was compiled in a text compilation and sorted by the main topics of interest covered below.

N fixation and relevance for planted forests

Rates of N fixation depend on interactions between the plant and bacteria and the ecosystem conditions that influence this activity. Ecosystem conditions include climate, soil characteristics, nodulation efficacy, mycorrhizal status, and management factors, such as nutrient inputs, and forest management practices e.g., thinning to reduce shade (Nygren et al. 2012; Peoples et al. 2012).

There are two groups of N-fixing plants considered relevant for productive land sectors: plants in the family Fabaceae (legumes) and so-called actinorhizal plants which occur in several angiosperm families, each of which forms a symbiosis with a different type of N-fixing bacteria (Burns & Hardy 1975). The bacterial species associated with the Fabaceae are diverse and are collectively known as rhizobia. The Fabaceae family is comprised of nearly 20,000 species in 780 genera that occur as herbs, shrubs, vines, or trees (Plants of the World Online 2022). Actinorhizal symbioses, all involving association with bacteria in the genus *Frankia*, are much less studied (Nygren et al. 2012). Examples of actinorhizal plants include alder (*Alnus* spp.), she-oaks (*Casuarina* spp.), and the New Zealand native plants tutu (*Coriaria* spp.) and matagouri *(Discaria toumatou* Raoul) (Silvester 1977).

Nitrogen-fixing plants can be established in planted forests following various strategies: as an understorey, as an overstory mixture, or as a rotational crop (Turvey & Smethurst 1983a). Understorey N-fixing plants are at their most productive during the first part of the forest rotation until canopy closure. At canopy closure, they become less competitive and eventually die off due to receiving insufficient light but supplying further N to the system via decomposing biomass. Another approach is to use overstorey mixtures which involve the establishment of a N-fixing tree species in combination with the main plantation tree (e.g., *P. radiat*a) and may supply a continuous input of N (Turvey & Smethurst 1983a).

Rotational N-fixing regimes involve scenarios where a N-fixing species is grown in the interval between harvest and the establishment of the next tree crop. Examples include oversowing with N-fixing plants to prevent weed invasion before re-planting with *P. radiata* (West & Dean 1992). Nitrogen-fixing weeds, such as gorse, that heavily infest a site and are removed before tree planting, could also be considered a type of rotational N-fixing regime, albeit unintentional.

Criteria for selection of N-fixing plants suitable for planted forests

Successful establishment of N-fixing plants requires matching species to the planted forest site characteristics and the forest management goals and operations. The criteria used in this review (see Table 1) for selecting N-fixing plants are based on those by Turvey and Smethurst (1983). These criteria include tolerance of site conditions and the ability to fix N for recycling in the ecosystem. We consider if the plant establishes easily, has potential to become a weed or invasive species, is susceptible to pests and diseases, whether seed is readily available and whether it could compete with the primary tree crop for water, light or other nutrients (Forrester 2014).

New Zealand planted forest soils cover a range in soil fertility and are often naturally acidic (Watt et al. 2008; Forrester 2014; Beets et al. 2019; Garrett et al. 2022) which is often associated with an increase in exchangeable aluminium. Aluminium toxicity can severely impair the establishment, yield and persistence of some plants (Morton & Moir 2018). Low levels of phosphorus (P) can also limit the growth of N-fixing plants (Moir et al 2016). Shade tolerance is important for an understorey regime but not necessary for a rotational regime with areas of clear-felling. Resistance to pests and diseases is another important factor that can affect successful establishment (Alma 1977; Dick 1994). Warming global temperatures and extreme events will place more importance on species that are drought tolerant and contribute to land stability (Lambie et al. 2018). Climate change and warmer temperatures will accelerate insect development and increase the susceptibility of host plants to attack (Watt et al. 2019).

Mixtures of trees (i.e., of N-fixing species and non-N-fixing species) may have additional advantages in forestry with respect to biodiversity, non-timber forest products and forest health over monocultures (Liu et al. 2018).

Potential N-fixing plants and trees for planted forests in New Zealand

In this section, we summarise N-fixing species that have been studied in New Zealand planted forests or agriculture and other N-fixing species not studied extensively but that could be suitable for New Zealand planted forests, targeting the criteria outlined above (Table 1). We included understorey exotic N-fixing plants and shrubs, many of which have been studied in association with New Zealand planted forests as well as some N-fixing trees and New Zealand native plants that have not been studied extensively within the planted forest context.

Exotic N-fixing understorey plants and shrubs

***Trifolium* spp.** (clovers) are among the most important and widely grown legumes for forage production and the improvement of soil fertility in temperate regions of the world (Ravagnani et al. 2012).

Trifolium repens L. (white clover) is the dominant legume for New Zealand's pastoral agricultural sector, recognised for its nutritional value, productivity, seed production and ability to fix N (Caradus et al. 1995). N fixation rates from 17 kg N ha^{-1} yr^{-1} to 380 kg N ha^{-1} yr^{-1} have been reported, varying with moisture stress, soil fertility, grazing, temperature and grass competition (Caradus et al. 1995).

Trifolium repens has poor persistence in dry conditions due to its shallow root system which is susceptible to moisture stress (MacFarlane et al. 1990). Other clovers are more resistant to drought conditions (Caradus et al. 2022). *Trifolium ambiguum* M.Bieb. (Caucasian clover) has a large root system and is favourable in agricultural systems that are exposed to drought conditions (Black & Lucas 2000). *Trifolium arvense* L. (haresfoot clover) grows in semi-arid parts of New Zealand and fixes N in dry, cold environments (Boswell et al. 2003).

Other clover varieties present in pastoral systems, but on a limited scale, include *T. pratense* L. (red clover), *T. subterraneum* L. (subterraneum clover) and *T. michelianum* L. (balansa clover) (Charlton & Stewart 1999). Seeds of some of the less known clover cultivars, more suited to low fertility soils, are not always commercially available (Monk et al. 2016). Non-commercial, adventive clovers have been shown to persist in less fertile areas of New Zealand (Boswell et al. 2003).

Low pH, low phosphorus (P) and aluminium (Al) toxicity can limit the growth of some clover species. The failure of *T. repens* and *T. pratense* to establish on granite-derived soils under areas of planted forest in the Nelson region was attributed to low pH and poor tolerance to Al (Gadgil 1983). All clover species respond positively to lime additions; this is primarily driven by improved tolerance to soil exchangeable Al (pH effect of lime). Glasshouse experiments have demonstrated that adventive annual clovers are well adapted to low pH and low fertility soils (Maxwell et al. 2012; Morton & Moir 2018). *Trifolium* spp. do vary widely in P-use efficiency and consequently some clovers have been identified that tolerate low P conditions (Moir et al. 2016).

Clovers can be susceptible to many pests and diseases (Woodfield & Caradus 1996). This area has received much research in New Zealand and there is a large body of information and understanding about pests and diseases relating to clover. Pests include the New Zealand grass grub (*Costelytra zealandica*), clover root weevil (*Sitona lepidus*), various nematodes and porina moth (*Wiseana* sp.) (Zydenbos et al. 2011). Management strategies include biological control and breeding programmes focussed on disease resistance (Fitzgerald 1981; Gerard et al. 2017).

In New Zealand, clover species have been used to prepare sites for forest planting. *Trifolium repens*, *T. pratense* and *T. subterraneum* were established on gold dredge tailings on the West Coast, South Island to improve soil fertility before planting *P. radiata* (Mead et al. 1980; Fitzgerald 1981). All clovers were able to establish without P fertiliser additions, and growth was improved with P addition (Mead et al. 1980). *Trifolium repens* established well in mixtures with maku lotus (*Lotus pedunculatus* Cav.) at trial sites in Kaingaroa forest and Mamaku forest with P addition (West et al. 1988). These trials, however, demonstrated that clover is less able to re-colonise areas with slash and other woody debris compared to maku lotus (West et al. 1991). Weed control is likely to be important in clover maintenance. Gadgil (1983) noted that *T. pratense* and *T. subterraneum* established well on a cleared site but were smothered by gorse within 2-3 years. Both *T. repens* and *T. patense* established well in trials under mid-rotation *P. radiata* but the ability to determine the effect on tree productivity was confounded by possum and deer browsing (Gadgil et al. 1986; Gadgil et al. 1988).

Nitrogen fixation of different grass and clover mixes was measured under two-year-old *P. radiata* in the Canterbury region of New Zealand (Goh et al. 1996). A seasonal effect was evident in the trial with the highest N fixation rates in spring and lowest in winter; tree shading and moisture stress also impacted N fixation rates with lower amounts in the pasture mixes located closest to trees. The percentage of N derived from N fixation was considerable for all clover grass mixes, thus the net N demand from the soil was low, particularly in summer (Goh et al. 1996).

Clover has been used successfully to increase soil fertility under *P. radiata* in South Australia. Waring (1966) described a field trial comparing the N-fixing abilities of *Trifolium* spp. to urea (applied at 735 kg ha^{-1}) to supply N to *P. radiata* on a second rotation soil with low fertility. A mixture of ten varieties of clover seed was sown two months before planting the tree seedlings and established quickly with *T. repens* dominating the sward. Before planting, the litter and logging slash were removed and a basal dressing of lime and superphosphate was applied. Average N fixation rates of 96 kg N ha^{-1} yr^{-1} were

TABLE 1: Criteria for selection of suitable N-fixing plants and ratings of N-fixing species

Plant species	**Common name**	**Tolerance to soil and site conditions**[a]					**N-fixation rate in planted forest**[c]	**Un-palatable**[d]	**Resistance to pests and diseases & availability of management strategies**[e]	**Minimal invasive risk**[f]	**Other economic and ecosystem benefits**	**Suitability to forestry operations**
		Low P	**Acidic soils**	**Shade**[b]	**Drought**	**Frost**						
Trifolium spp.	Clover	Species dependent					🟩	🟨	🟦	🟦	Forage for bees	🟦 Site prep and ongoing weed and pest control
Lotus spp.		🟩	🟩	🟩	Species dependent	🟩	🟩	🟨	🟦	🟦		🟩 Pest control; will establish on forest slash
Medicago sativa	Lucerne	🟨	🟨		🟩		🟩		🟦	🟦	Biofuel; fodder	Fertiliser
Lupinus spp.	Lupin	🟩	🟩	🟨	🟩		Species dependent	🟩		🟨		🟩 Managed to remain within forest boundaries
Cytisus scoparius	Broom	🟦	🟦	🟨	🟩	🟩	🟩	🟩	🟩	🟨		🟨 Hinders accessibility
Ulex europaeus	Gorse	🟩	🟩	🟨	🟩	🟩		🟩	🟩	🟨		🟨 Hinders accessibility; potential to increase fire risk
Lathyrus latifolius	Everlasting pea	🟩	🟦	🟩	🟩	🟩	🟩			🟨		Managed to remain within forest boundaries
Dorycnium spp.	Hairy canary clover	🟦	🟩		🟩	🟩	🟩	🟨			Forage for bees	Good fire resistance
Ornithopus spp.	Serradella	🟩	🟩		🟩	🟩		🟨	🟩			Initial weed control
Coronilla varia	Crownvetch	🟦	🟨	🟦	🟦	🟩			🟩			Initial weed control
Vicia spp.	Vetch	🟩	🟩	🟩	🟩	🟩	🟩	🟨	Species dependent			Initial weed control
Acacia melanoxylon		🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟨	Produces valuable timber & non timber products	Managed to remain within forest boundaries

TABLE 1 continued: Criteria for selection of suitable N-fixing plants and ratings of N-fixing species

Plant species	**Common name**	**Tolerance to soil and site conditions**[a]					**N-fixation rate in planted forest**[c]	**Un-palatable**[d]	**Resistance to pests and diseases & availability of management strategies**[e]	**Minimal invasive risk**[f]	**Other economic and ecosystem benefits**	**Suitability to forestry operations**
		Low P	**Acidic soils**	**Shade**[b]	**Drought**	**Frost**						
Alnus spp.		🟩	🟩	🟩	🟩	🟩			🟦	🟧	Erosion control; timber	Managed to remain within forest boundaries
Casuarina spp.		🟩	🟩	🟩	🟩	🟩		🟧	🟧	🟧	Fuel wood	Unknown if inoculation is necessary
Chamaecytisus palmensis	Tagaste	Responds to P	🟦	🟧	🟩	🟦		🟧	🟦	🟦	Nectar; pollen; wood fuel; soil conservation; nursery crop; food for native birds	🟦 Horizontal spread; pest control until established
Carmichaelia spp.	New Zealand brooms				🟩	🟩		🟧			Biodiversity	Ongoing weed and pest control
Clianthus spp.												
Sophora spp.	Kōwhai			🟦	🟦	🟩					Biodiversity	Nectar toxic to honey bees
Coriaria spp.	Tutu	🟩	🟩	🟩	🟦	🟦						Seeds, berries, sap and honeydew are toxic to people and honey bees
Discaria toumatou	Matagouri	🟧		🟦							Firewood; honey	Thorny

Guide to species rating by variable: white = insufficient data; green = good; blue = moderate; orange = poor

[a] Tolerance information from Pollock (1986) and Van Kraayenoord and Hathaway (1986). Environmental tolerance may vary within a species and time of year. Tolerances depend on growth stage, and adaptation or acclimatisation to a particular climate.

[b] Shade tolerance was rated good if it had previously established well under mid-rotation, 250 stems/ha radiata pine (Gadgil et al 1986 & 1988).

[c] Nitrogen fixation rate was rated good if > 50 kg N ha^{-1} yr^{-1}. Nitrogen fixation rates will differ over environmental tolerance range. For references and information on N-fixation rates see Supplemental Dataset S1.

[d] Rated good if not palatable to pests (e.g. rabbits, possums).

[e] Resistance to pest and diseases was rated moderate if management strategies were available

[f] Invasiveness risk was rated moderate” if plant species is an exotic N-fixer (Daehler 1998) and “poor” if escape risk is high i.e., can establish persistent self -sustaining populations with spread far from parent plants.

estimated three years after establishment. Increased height and growth of pines were observed during the second growing season and increased foliar N levels after three years indicating that the pool of N available to the pines had increased. Initially clover was a very vigorous competitor particularly during periods of lower rainfall. At the end of seven years growth there was no difference in size between the trees treated with clover or those treated with urea but all were significantly larger than untreated control trees (Waring 1966; Waring & Snowdon 1985).

Turvey and Smethurst (1983a) in their review on N-fixing plants in forest plantation management describe several overseas studies using clover species as a rotation planting or underplanting, with different tree species. Clover appeared to increase soil fertility in most of these studies but benefits to tree growth were more varied; some reported improved growth some reported depressed growth and in others, effects on tree growth were not reported.

Clover can provide additional benefits by providing nectar and pollen for honeybees (Goulson & Hanley 2004). For example, white clover honey production contributes approx. $25 million in export receipts for New Zealand (Caradus et al. 1995).

Trifolium spp. can establish well under *P. radiata* and have been shown to fix N at rates that produce a meaningful impact on *P. radiata* productivity (Waring & Snowdon 1985). Information on best application practices is readily available for commercial cultivars. Cultivars with improved phosphate efficiency, N fixation and drought tolerance are gaining interest for use in lower input agricultural systems in semi-arid and marginal environments. Due to their palatability, browsing by deer, possums and other pests can be an issue in forestry situations. Selection of cultivars best adapted to the site conditions is important and a mix of plants is a good option to cover site and seasonal variability. Some site preparation (removal of woody debris, fertiliser dressings) and ongoing weed and pest control is needed.

Lotus corniculatus **L.** and ***Lotus pedunculatus*** **Cav**., are two introduced *Lotus* species that are now naturalised in New Zealand (Popay et al. 2010). *Lotus corniculatus* (birdsfoot trefoil) has been promoted for use in drier regions (Nordmeyer & Davis 1976; Charlton & Belgrave 1992; Douglas et al. 2004; Monk et al. 2016).

Lotus pedunculatus is a perennial with a rhizomatous growth habit (Monk et al. 2016). Maku lotus (*Lotus pedunculatus* Cav.) was developed as a tetraploid cultivar by Grasslands DSIR (Armstrong 1974). Other cultivars with improved establishment vigour have been developed for release in New Zealand (Monk et al. 2016; Nichols et al. 2016).

Lotus pedunculatus is sown as a pasture species in New Zealand high country and low fertility grasslands (Lancashire et al. 1979; White 1995) and in New Zealand planted forests (Brockerhoff et al. 2003; Monk et al. 2016). Lotus is tolerant of low P and acidic soils (range pH 4.6 – 6.5) (Lowther 1980; Morton 1980; Simpson et al. 2014; Moir et al. 2016) and can fix large amounts of N; 410 kg N ha^{-1} yr^{-1} with low applications of P (one application of 25 kg P ha^{-1}) and 590 kg N ha^{-1} yr^{-1} with large applications of P (112 kg P ha^{-1} yr^{-1}) (Brock 1973). Lotus is one of the more shade tolerant legume species (Gadgil et al. 1986; West et al. 1991; Balocchi & Phillips 1997; Devkota et al. 1997) although shade may result in reduced N fixation rates (Butler et al. 1959). Moderate annual rainfall (greater than 600 mm) appears to be the most important climatic requirement (Lancashire et al. 1979).

In *P. radiata* forest, *L. pedunculatus* established well in comparison with 35 legumes in pumice soil in the, central North Island New Zealand (Gadgil et al. 1986). Other lotus cultivars including *Lotus* hybrid G4712, *L. uliginosus* G4703 were also successful in this trial. Fertiliser was not used and weed control was minimal, with only woody shrubs removed. Soil fertility or tree growth was not measured; however, the authors concluded that a low level of N fixation could be expected after three years of unmanaged growth (Gadgil et al. 1988).

The persistence of *L. pedunculatus* under *P. radiata* has been demonstrated in large-scale oversowing and grazing schemes at Maramarua, Waiuku and Kaingaroa forests in the North Island established between 1981 and 1985 (Brown 1988; Dale & Todd 1988; West et al. 1988; West et al. 1991; West & Dean 1992). N fixation in these oversowing trials was not quantified but appeared substantial as tree basal area responses of 16% occurred over a period of eight years in the Kaingaroa trial for the ungrazed *L. pedunculatus* treatment (West & Dean 1992).

Large scale use of *L. pedunculatus* in central North Island forests resulted in significant defoliation of young *P. radiata* by the insect pest *Helicoverpa armigera (synonym Heliothis armigera)* (Alma 1977). This occurred in summer when *Helicoverpa* populations developed over large areas oversown with *L. pedunculatus*. Following defoliation of the *L. pedunculatus*, the large population of *Helicoverpa* transferred to *P. radiata*, causing defoliation of trees. Due to the negative effects of the insect on radiata pine, oversowing with *L. pedunculatus* became unpopular and was widely discontinued. Today, biological control and insecticides are available to control outbreaks (Cameron et al. 2006; Bain et al. 2009) but these innovations have not resulted in the resumption of oversowing with Lotus. *Lotus pedunculatus* is resistant to grass grub (*Costelytra zealandica*) and porina caterpillar (*Wiseana cervinata*) (Farrell et al. 1974; Sutherland 1975) both of these pests cause significant losses to clover-based pastures in New Zealand each year (Caradus et al. 2022).

In a coastal sand dune forest on the west coast of the North Island, *L. pedunculatus* performed poorly compared to other legumes in the study due to low moisture levels, accumulating above-ground amounts of 55 kg N^{-1} yr^{-1} (Wanjiku et al. 1997). *Lotus corniculatus* is more tolerant of low moisture levels than *L. pedunculatus*, making it suitable as a special-purpose legume cover crop in drought-prone, infertile regions (Charlton & Stewart 1999).

Lotus pedunculatus has many characteristics suitable for a *P. radiata* understorey. Despite significant use of this legume in *P. radiata* forests in the North Island, there has been little data collected on its ability to increase soil N levels and improve *P. radiata* productivity. Also, issues associated with management of *H. armigera*, the performance of lotus cultivars under drier conditions and optimal P requirements require further investigation.

Medicago sativa **L.** (lucerne) is a perennial legume, typically grown in dry conditions for grazing or hay/silage, where it outperforms ryegrass/white clover pasture (Moot 2012). *Medicago sativa* is adapted to dry conditions as the crop has a strong tap root and is capable of utilising water deep from the soil profile (Moot et al. 2008) and has been identified as a potential biomass crop for biofuel production in New Zealand (Kerckhoffs & Renquist 2013). N derived from N fixation for *M. sativa* shoots, ranged from 17–90% (proportion of legume N derived from atmospheric N), equivalent to 2–284 kg N $ha^{-1}yr^{-1}$ in Australian pasture experiments (reviewed in (Peoples et al. 2012).

Medicago sativa is susceptible to pests and diseases including aphids, weevils, nematodes, alfafa mosaic virus and various fungal and bacterial diseases (Close et al. 1982; McNeill et al. 2021). Pest and disease susceptibility of *M. sativa* has been reduced through breeding and management strategies (Purves & Wynn-Williams 1989). Lime applications may be required for optimum growth as *M. sativa* does not grow well in acidic soils with high Al levels (>3 mg kg^{-1}) (Moir et al. 2016).

Using *M. sativa* under *P. radiata* in New Zealand led to an N fixation rate of 230 kg N $ha^{-1}year^{-1}$ (Goh et al. 1996). The net N demand from the soil was greater for *M. sativa* than clovers during the spring/summer period when *M. sativa* derived only 72% of its N from N fixation compared with 83–97% with clovers (Goh et al. 1996). This was a cut and carry trial (fixed N was removed) so results may not be relevant to a forestry setting where N inputs result from decomposing biomass.

Two-year-old *P. radiata* trees in Canterbury (annual rainfall at site = 660 mm) demonstrated decreased height and diameter in a cut and carry trial of *M. sativa* compared to a bare ground control (no competition) (Mead et al. 1993). At age ten years, the differences in *P. radiata* growth between the lucerne understorey and the bare ground control were diminished (Peri et al. 2002). To reduce competition, careful selection of *P. radiata* genotypes can be beneficial as demonstrated by improved growth of clonal *P. radiata* and *M. sativa* compared to seedling *P. radiata* and *M. sativa* (Gautam et al. 2003).

As far as we are aware, the use *M. sativa* in New Zealand to improve radiata pine growth has only been assessed in the cut and carry studies mentioned above. More research particularly on strategies to manage the competition between *M. sativa and P. radiata* for N and water are required before *M. sativa* could be considered a good option for underplanting in a New Zealand planted forest. The potential for *M. sativa* to provide greater benefits to *P. radiata* by leaving decomposing biomass within the system is an option that could be evaluated, although this option appears to be less economically favourable due to loss of earnings from *M. sativa* as a secondary crop.

The genus ***Lupinus*** has over 600 accepted species (Plants of the World Online 2022). *Lupinus arboreus* Sims (yellow tree lupins), *L. angustifolius* L. (blue lupins) and *L. polyphyllus* Lindl. (Russell lupins) are considered in more detail below. Lupins can grow on acidic subsoils (pH 5.0), in the presence of high levels of soluble Al and limited supplies of P (Davis 1981a, 1981b, 1991). There is a wide range of palatability in the genus, depending on the level of alkaloids, from highly palatable to non-palatable. While some lupin cultivars have been bred to improve palatability (Millner et al. 2004), other less palatable cultivars have been tested with success for protecting tree seedlings from browsing animals (A. M. Miller et al. 2006a).

Lupinus arboreus was established extensively in northern New Zealand coastal areas to stabilise sand dunes, but benefits for soil fertility were also recognised, providing an opportunity to support *P. radiata* forests (Gadgil 1971). The lupins in these sand dune areas were grown for about three years before being crushed, or sprayed with herbicides, to allow pine establishment. They regenerated and persisted until canopy closure, then declined until regenerating again at each thinning, fixing at least 160 kg N ha^{-1} yr^{-1} for open stands of lupin (Gadgil 1971) (Figure 1). Nitrogen fertiliser without *L. arboreus* was insufficient to meet the N demands of the tree crop due to low levels of N fertiliser retention in the sandy soil (Jackson et al. 1983; Gadgil et al. 1984). Benefits to long-term growth of *P. radiata* were demonstrated (at 12 years after lupin die-off), although this was affected by moisture levels (Beets & Madgwick 1988). At mid-rotation (age 17 years) in these low-N and sandy ecosystems, the combination of N fertiliser and *L. arboreus* can support higher growth rates and N biomass accumulation (Baker et al. 1986; Beets & Madgwick 1988) (Figure 1). N fixation rates of 80 kg N ha^{-1} y^{-1} (average over 5 years) were recorded in the same forest, with lupin growing under a developing *P. radiata* canopy (Baker et al. 1986). Establishment of *L. arboreus* has also been demonstrated on yellow-brown pumice soils in the central North Island in a 10-year-old *P. radiata* stand (Gadgil et al. 1986); however, N fixation was not measured.

At sites with low moisture, *L. arboreus* can compete with *P. radiata* for water. Smethurst et al. (1986) found *L. arboreus* led to high mortality of *P. radiata* seedlings and no growth response of survivors on a sandy podzol soil in Victoria, Australia.

The use of *L. arboreus* in New Zealand forestry ceased in the 1990s due to lupin blight disease destroying 90% of the *L. arboreus* population. The disease is caused by a fungus (*Colletotrichum gloeosporioides*) which causes rapid mortality of seedlings, and dieback and cankering of older plants (Dick, 1994*). Helicoverpa armigera* also defoliates yellow lupins (Bain et al. 2009).

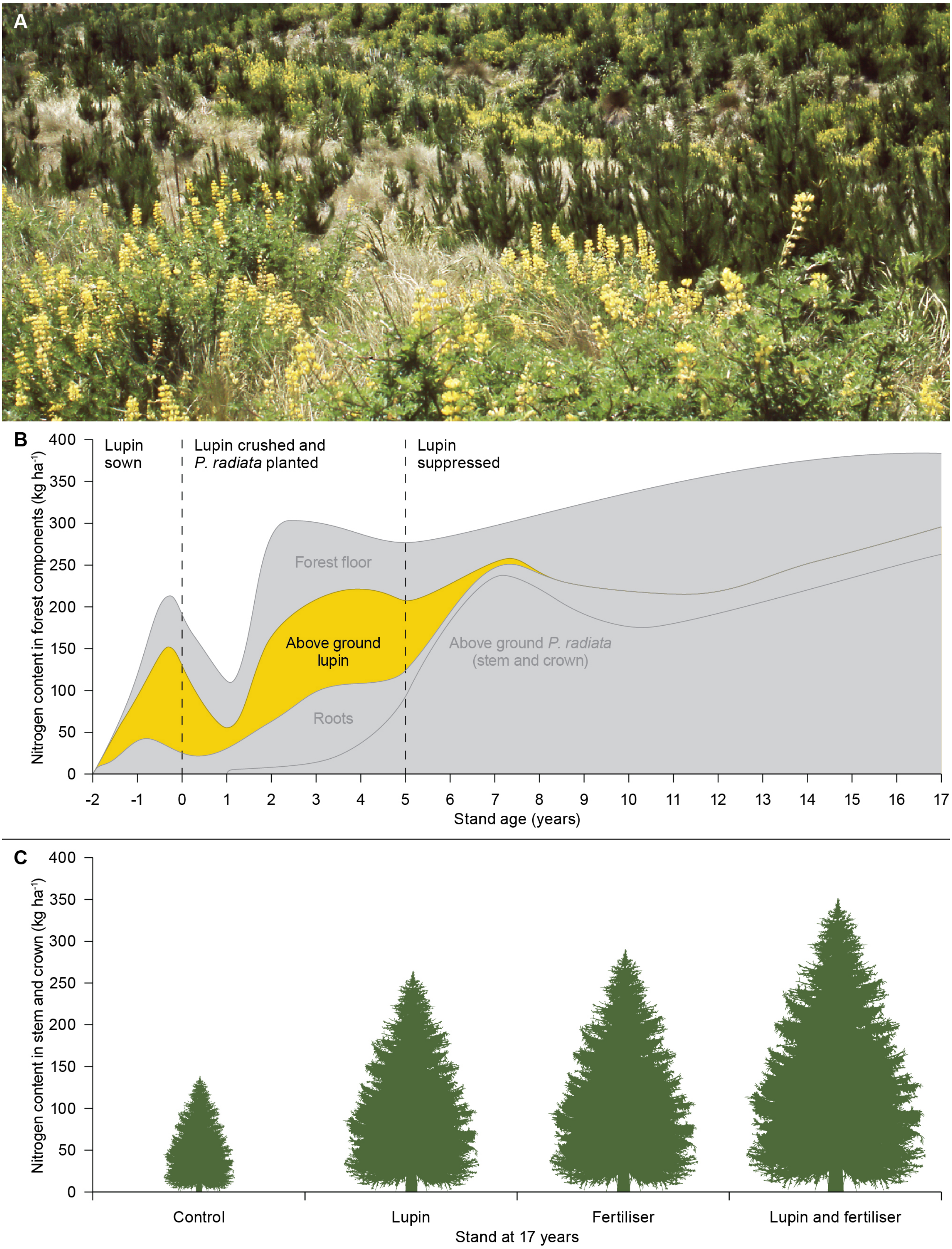

FIGURE 1: The effect of lupins and mineral fertiliser on nitrogen content of forest components in a first rotation sand dune forest (Trial AK287). (A) Photograph of lupins in an early-rotation forest stand. (B) Changes in N content with stand age showed that lupins stored N and then, when they were suppressed (by increased canopy cover), N was released, which was used by the growing forest. (C) Treatment of lupins, fertiliser, and lupins plus fertiliser increased the growth and nitrogen accumulation in the above-ground tree biomass compared to the control. Adapted from Beets et al. 1988 and Beets and Madwick (1988).

Lupinus angustifolius (blue lupins) and ***Lupinus polyphyllus*** (Russell lupins)

Lupinus angustifolius, an annual which mainly grows during winter to spring, was introduced to the South Island of New Zealand in the 1940s to improve soil N status and as a source of high-quality feed for sheep (Vellasamy et al. 2000), but more recently was investigated for use in *P. radiata* plantations in New Zealand (Millner et al. 2004). Cultivars with resistance to lupin blight were released in New Zealand in 2003 (Millner et al. 2004) but no further record of their use in New Zealand planted forests was found in the literature surveyed.

Lupinus angustifolius was planted as an understorey with *P. radiata* in Australia with limited success in one trial (Smethurst et al. 1986). The N-fixing rate of *L. angustifolius* was 37 kg N $ha^{-1}yr^{-1}$ and the growth of *P. radiata* was similar to that of the trees with herbicide only. The best growth of *P. radiata* occurred without lupins, with fertiliser and weed control (Smethurst et al. 1986). More success was evident in another trial with *L. angustifolius* where, although *L. angustifolius* increased the water stress in pines on several occasions, the overall effect of *L. angustifolius* was beneficial (16-32% increase) in *P. radiata* stem growth (Nambiar & Nethercott 1987). Problems encountered with infestations by brown leaf spot (*Pleiochaeta sitosa*) and *Fusarium* spp. were solved with the use of a different cultivar more resistant to fungal attack (Nambiar & Nethercott 1987).

Lupinus polyphyllus has been used as a revegetation species for degraded areas (Nordmeyer & Davis 1976) and was identified as a potential forage crop in New Zealand high country grazing systems (Scott 2014). However, limited commercial seed supply (Monk et al. 2016) and debate about planting this lupin in the high country due to its invasiveness (P. Wardle 2016) has restricted its uptake.

Lupinus polyphyllus grows and persists in moderately acidic soils (pH <5.6) with low P and high exchangeable aluminium (Al>3ppm) (White 1995). Addition of sulphur may be a requirement in sulphur deficient soils (White et al. 1995). *Lupinus polyphyllus* is well adapted to moderate to high rainfall areas that experience water stress in summer (White 1995; Woodman et al. 1996).

Lupinus polyphyllus can fix large quantities of N (Davis 1991). Soils planted with *L. polyphyllus* in the South Island high country had greater total soil N (%) and soil mineralizable N (kg ha^{-1}) compared to adjacent pasture soils (Che et al. 2018). Both *L. polyphyllus* and *L. angustifolius* showed indications of increasing *P. radiata* tree height and foliage N levels in a trial to rehabilitate gold dredge tailings in river flats, South Island, New Zealand (Fitzgerald 1981).

Lupins *(L. polyphyllus*, *L. arboreus, and other* species*)* have become invaders in Europe, New Zealand and Australia (Hiltbrunner et al. 2014). The plant seeds readily and spreads several metres, often germinating at quite low temperatures, while a proportion remains dormant initially, germinating in later years. The seeds are also dispersed along waterways, transporting them large distances from the parent plant (P. Wardle 2016; Environment Canterbury 2018). *Lupinus polyphyllus* is present on both the Environment Canterbury Declared Pests list and the DOC Consolidated Weed List (Howell 2008) and specific rules need to be met concerning this pest in some regions of New Zealand.

Harvey et al. (1996) surveyed pathogens of *L. polyphyllus* in New Zealand. Yellow tree blight (*C. gloeosporioides)* results in less severe die-back in *L. polyphyllus* as plants produce new shoots the following season; however, crown and root rot, caused by *Fusarium heterosporum,* were a major cause of plant death in a New Zealand field trial (Harvey et al. 1996).

Lupins can tolerate simultaneous P and N deficiencies and it has been proven that they increase soil fertility, benefitting *P. radiata* productivity. Nitrogen-fixing rates under different conditions have not been well characterised for species other than *L. arboreus*. Caution near waterways and sensitive environments is required because lupins are a significant risk to biodiversity. A level of forest management (thinning) is required to maintain lupin growth and N fixation because they are shade-intolerant (Beets & Madgwick 1988).

***Lathyrus latifolius* L.** (everlasting pea) fixed the highest amount of N (214 kg N $ha^{-1}year^{-1}$) under *P. radiata* in a legume screening study exploring candidates to replace yellow lupins (Wanjiku et al. 1997). However, *L. latifolius* was not considered a suitable replacement because of its weed potential arising from its scrambling growth habit (Douglas et al. 2004).

***Dorycnium hirsutum* L.** (hairy canary clover) grows well on low fertility soils under cold, dry conditions. However, heavy, wet soils are not tolerated (Wills et al. 1989). *Dorycnium hirsutum* is a low-growing, perennial shrub (maximum recorded height over 4.5 years = 74 cm) and as such is unlikely to be an obstruction to forestry operations (Douglas et al. 2004). It provides forage for bees as well as stock (Wills et al. 1989). Good N fixation rates have been demonstrated; *D. hirsutum* fixed 71 kg ha^{-1} $year^{-1}$ in a New Zealand coastal sand dune soil (Wanjiku et al. 1997), while comparable results and tolerance to a range of coastal conditions were observed in a similar trial (Douglas et al. 2004). The invasiveness of this species has been identified as low, but restricted seed availability prevents widespread use (Tozer et al. 2021).

Four annual ***Ornithopus* spp**. (serradella) occur in New Zealand. *Ornithopus pinnatus* (Mill.) Druce is the dominant species in Northland and has spread to less fertile, sandy coastal soils. Another species, *O. perpusillus* L. (wild serradella) occurs as a small prostrate plant in dryland pastures on the volcanic plateau around Rotorua and Taupo (Roy et al. 2004). The other two species, *O. sativus* Brot. (pink serradella) and *O. compressus* L. (yellow serradella) are recognised as having potential value as herbage legumes (Charlton 1983). Grasslands Koha' pink serradella performs well on light, acid, sandy soils, where its deep rooting system makes it less susceptible to short droughts than subterranean clover (de Lautour & Rumball 1986). It is competitive against weed invasion and free from any serious pests and diseases (de Lautour & Rumball 1986). *Ornithopus* spp. were assessed in trials in radiata pine forests near Rotorua (Gadgil 1983; Gadgil et al. 1988) and were identified as an option for forest oversowing on warmer and drier sites (West & Dean 1992). Seed availability in New Zealand is restricted (Charlton & Belgrave 1992), preventing its use.

***Coronilla varia* L.** (crownvetch) is a hardy, persistent perennial legume that spreads by underground creeping roots. In New Zealand, it is summer productive and winter dormant, most suited to fertile soils of pH>6, although once established it will tolerate acidic soils. Tolerant of heavy frosts and drought, it is also relatively pest and disease resistant. It is slow and difficult to establish from seed, enabling weeds and companion species to easily outgrow and compete with seedlings (Charlton 1983; Gadgil et al. 1986).

***Vicia* spp.** (vetch), demonstrated good growth and relatively good N fixation rates when compared with other legumes, in the absence of weed competition, under mid-rotation *P. radiata* (Gadgil et al. 1986).

***Cytisus scoparius* (L.) Link** (broom) is a shrub, widespread throughout New Zealand planted forests (Richardson 1993). Broom colonises open environments, including those that are deficient in soil water and N. It is fast-growing, has dry climate adaptions and produces large quantities of seed (Williams 1981; Watt, Clinton, et al. 2003). Broom is considered a troublesome weed species in the forestry industry, found to cause severe competition for light and water and reduce volume growth in juvenile *P. radiata* (Richardson et al. 1996; Watt, Whitehead, et al. 2003). Annual fixation of 111 kg N ha^{-1} yr^{-1} into above-ground tissues of broom was demonstrated under *P. radiata* and transfer of this fixed N from broom to *P. radiata* was considered likely (Watt, Clinton, et al. 2003). However, the authors concluded that competition by broom for water outweighed any beneficial influence on the tree resulting from N transfer. Long-term benefits to *P. radiata* are most likely on wet, N-deficient sites (Watt, Clinton, et al. 2003).

Ulex europaeus (gorse), like broom, is a widespread, invasive, leguminous species in New Zealand. Gorse grows well on steep, infertile land. Magesan et al. (2012) review N cycling in gorse-dominated New Zealand ecosystems and estimate N fixation rates vary from 20 – 200 kg N ha^{-1} yr^{-1} for gorse. In planted forests, gorse can make access difficult for pruning and thinning operations. Gorse competes with trees for light, nutrients and water reducing stand quality and growth rates (Richardson et al. 1996; Magesan et al. 2012). Eighteen years after planting *P. radiata* in Ashley Forest (South Island, New Zealand), stands with good gorse control had greater merchantable volume of 173 m^3 ha^{-1} compared to 85 m^3 ha^{-1} for stands with conventional gorse control for 1 year (Balneaves & McCord 1990). Gorse stands can increase fire risk with very dry foliage over the summer months. Gorse is identified as a potential biomass crop for New Zealand due to its wide adaptation, growth on sloping marginal land, coppicing ability and need for little or no fertiliser (Kerckhoffs & Renquist 2013).

Exotic N-fixing trees

The genus ***Acacia*** *(tree wattles)* includes about 1350 species belonging to the genus *Acacia*, exhibiting variations in size, structure, and adaptation to site conditions (Brockwell et al. 2005). *Acacia* species are grown for wood products (timber, furniture making, wood pulp, sawdust) and non-wood products (gums, tannins, edible acacia seeds, pollen for honeybees, animal forage, perfume manufacture) (Brockwell et al. 2005). *Acacia* have potential as a short rotation bioenergy crop due to high wood density and high growth (P. Hall 2013). *Acacia* species introduced to New Zealand for silviculture include *A. mearnsii* De Wild. (black wattle), *A. dealbata* Link (silver wattle) and *A. melanoxylon* R.BR. (Tasmanian blackwood). Most were originally planted on farms for firewood, soil conservation or quick-growing shelter.

Suitable habitats range from arid areas of low seasonal rainfall to moist forests and riverbanks with a wide variety of soil types (Brockwell et al. 2005). N fixation rates for *Acacia* range from 0 – 200 kg N ha^{-1} yr^{-1} but are generally at the lower end of this scale (Brockwell et al. 2005). N fixation of *Acacia* spp. can be improved via rhizobial inoculation of seedling stock in nurseries and other development methods (Brockwell et al. 2005).

Acacia species are susceptible to nematodes, fungal pathogens and insect pests (Brockwell et al. 2005). Biological control can reduce the impact of some of these pests (Murray & Withers 2011).

Acacia spp. have been planted to enhance soil N and increase the productivity of *Eucalyptus spp.* in tropical environments (see ref within Forrester et al. 2006; Paula et al. 2018). However, this combination has not been studied in a New Zealand context. In New Zealand, increased soil N fertility has been demonstrated with monoculture plots of *A. dealbata* (Frederick 1985) and *A. melanoxylon* (Power et al. 2003). *Pinus radiata,* in southeastern Australia, demonstrated reduced growth with relatively low densities of *A. verniciflua* A.cunn and *A. terminalis* (Salisb.) J.F. Macbr. (Turvey et al. 1983b). Similarly, above ground growth of 5 yr-old *P. radiata* was reduced, near Canberra, Australia (annual rainfall = 625 mm) planted with *A. mearnsii* and *A. decurrens* (J.C.Wendl.) Willd. (Forrester et al. 2007).

Acacia spp. typically have very fast growth rates and rapidly occupy disturbed sites; therefore these species may present an increasing risk as a weed problem in New Zealand with climate change (Watt et al. 2019). Some species can coppice which makes them hard to control. Seed germination is often stimulated by fire, therefore increases in fire frequency and severity will make sites more predisposed to invasion by these species. Some *Acacia* spp. are already a localized problem in northern and eastern parts of the country (Watt et al. 2019). Eight species of Acacia, including *A. dealbata*, *A. mearnsii* and *A. melanoxylon* are considered environmental weeds in New Zealand (Howell 2008).

Overseas trials with selected *Acacia* spp. in regions of low rainfall show there is no benefit to *P. radiata* productivity due to strong competition. The weed potential for most *Acacia* spp. is high and containment will need consideration. There is currently no information available for mixed stands of *Acacia* spp. and *P. radiata* grown in New Zealand. *A melanoxylon* has been identified as a potential tree species for bioenergy production (P. Hall 2013) and erosion control (Phillips et al. 2015) which could add additional value.

***Alnus* spp.** (Alder) are deciduous, actinorhizal trees. Improved growth and ecosystem benefits have been demonstrated overseas in forests with alders mixed with *Populus* spp. (poplars) and *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir) (Binkley 1983; ND Turvey & Smethurst 1983a; Lavery et al. 2004; Marron & Epron 2019). *Alnus* spp. introduced to New Zealand include *A. acuminata* Kunth (Andean alder), *A. rubra* Bong. (red alder), *A. glutinosa* (L.) Gaertn. (black or common alder), *A. cordata* (Loisel.) Duby (Italian alder) and *A. alnobetula* subsp. fruticosa (Rupr.) Raus (green alder) (Ledgard & Baker 1988).

Alders are grown in New Zealand as horticultural shelterbelts because of their vigorous growth when young which then slows after 4-5 years, allowing the crop tree to take over (Satchell 2018). *Alnus cordata* has been grown as a N-fixing nurse crop for *Sequoia spp.* in the Manawatu hill country, interplanted as every second tree (Satchell 2018). Alders have potential for “erosion control forests” because of their root development and below ground traits (Ledgard & Baker 1988; Phillips et al. 2015). *A. rubra* timber is easy to mill and season and “produces a stable, medium density, light brown timber suitable for panelling, joinery and furniture” (Satchell 2018).

Alder can grow well in poor soils, independent of both N and P, tolerating a wide range of site conditions; several species are also well adapted to colder latitudes and can thrive on wet sites (Silvester 1976). Some species e.g., *A. acuminata,* grow well on drier sites (Ledgard & Halloy 1991). *Alnus alnobetula* has been used extensively for soil improvement and stabilisation in the central European Alps but has been found to spread resulting in undesirable ecosystem transformations so is now considered a risk (Hiltbrunner et al. 2014). Alder can disperse down waterways and spread. In New Zealand, unmanaged *A. glutinosa* can develop into a thicket and become a problem weed (Popay et al. 2010).

Nitrogen fixation rates for alder range from 40 – 300 kg N ha^{-1} yr^{-1} (Silvester 1976). Artificial inoculation is unnecessary as there is widespread presence of bacteria capable of nodulating alder in New Zealand soils (Clawson et al. 1997). Alder exhibit an obligate N-fixing pattern which means they do not self-regulate when N supply becomes sufficient (Menge & Hedin 2009). This could result in increased nitrous oxide emissions and nitrate leaching if N fixation is not matched with biological demand (Bühlmann et al. 2014; Bühlmann et al. 2017).

Alders are susceptible to *Pseudomonas syringae* pv. *syringae* which causes leaf spot and cankers in alder in New Zealand (Spiers 1990). Poor weed control and animal damage (notably possums) can cause failure of alder to establish (Ledgard & Halloy 1991).

Growth of alders with *P. radiata* has not been reported. Alders offer secondary benefits in the way of a valuable timber and erosion control but have the potential to be invasive and may promote nitrate leaching and nitrous oxide emissions (due to their inability to self-regulate N fixation) if not managed well.

***Casuarina* spp.** (she-oaks) comprise about 45 species naturally occurring in Australia, Polynesia, Southeast Asia and India (Nicholas 1986). The main species planted in New Zealand are *C. cunninghamiana* Miq. and *C. glauca* Spreng. which are predominantly used for horticultural shelterbelts in warmer northern regions of New Zealand (Wilcox 1988). *Casuarina cunninghamiana* tends to open out at the base and is more palatable to grazing stock, rabbits, and hares. *Casuarina* spp. can colonise harsh sites and tolerate extremes of soil acidity, salinity, and water stress (both drought and flooding) (Bulloch 1994). Casuarina have a moderate growth rate under New Zealand conditions, and rank well in comparison to other fuel wood crop species for calorific value in relation to wood volume (J. Miller 1987).

Casuarina species fix N by an actinorhizal symbiosis. Some studies suggest that although some species can fix N, others do not develop root nodules without artificial inoculation (Bulloch 1994). N fixation rates of 40-62 kg N ha^{-1} yr^{-1} have been reported in mixed stands with *Eucalyptus* spp. (Gauthier et al. 1985; Parrotta et al. 1994). *Casuarina* can also form symbiotic associations with ectomycorrhizal fungi (EMF) and/or arbuscular mycorrhizal fungi (AMF) to enhance phosphate supply (Maity & Pawlowski 2021). Although some *Casuarina* spp. are considered invasive in parts of the world, the cooler climate and lack of suspected endemic inoculants mean this is not currently a problem in New Zealand.

Casuarina timber is suitable for furniture and crafts and is valued as a fuelwood and charcoal source (Silvester 1977). *Casuarina* may be an option for future environment needs (tolerance of poor fertility and low soil moisture). Research with *Casuarina* spp. has not progressed due to doubts about their ability to form successful microbial symbioses without artificial inoculation in New Zealand. Questions remain about their nodulation and their suitability for intercropping with *P. radiata*.

***Chamaecytisus palmensis* Prolifer subsp. *palmensis* (Christ) G.Kunkel** is a small (up to 5 m) evergreen, leguminous tree introduced into New Zealand for stock fodder and shelter (Townsend & Radcliffe 1990). The plant, commonly referred to as tagaste or tree lucerne, is common in lower North Island and coastal eastern South Island regions and is found in waste areas and along roadsides. *Chamaecytisus palmensis* grows well in drought-prone areas and adult plants are moderately frost tolerant (Newstrom-Lloyd & McPherson 2018). *Chamaecytisus palmensis* is highly palatable to sheep, goats, possums, hares, rabbits (Townsend & Radcliffe

1990). In a screening trial under mid-rotation pine near Rotorua, *C. palmensis* performed well (Gadgil et al. 1986) and in a coastal sand dune trial accumulated high levels of N (Douglas et al. 2004). It was identified as a potential nuisance to forestry operations due to its horizontal spread (more than 1 m within 2.5 years) (Douglas et al. 2004). In a forage trial in "moist" hill country, N fixation was estimated to be 128 kg N ha^{-1} yr^{-1} (Lambert et al. 1989). *Chamaecytisus palmensis* provides forage for bees, has potential for wood fuel or raw material for a specialist craft industry (J. Miller 1987; Newstrom-Lloyd & McPherson 2018). This species has moderate weed risk potential (Tozer et al. 2021) and displays some of the desired characteristics for combination with *P. radiata*.

Native N-fixing plants

The native legumes present in New Zealand are represented by four genera: *Carmichaelia*, *Clianthus*, *Montigena* and *Sophora*. Actinorhizal N-fixing families native to New Zealand include the genera *Coriaria* and *Discaria.* Many of the native N-fixing plants are of concern with respect to their conservation status which ranges from rare to endangered (de Lange et al. 2009). Limited information is available on N fixation rates for native N-fixing plants and their impact on *P. radiata* productivity and in most cases, N fixation has not been quantified.

***Carmichaelia* spp.** (New Zealand brooms) are distributed throughout New Zealand, often present in disturbed habitats on a wide range of soil types. The morphology of the species is remarkably diverse; there are trees, shrubs, and prostrate forms (Thomas & Spurway 2001). Of the 23 New Zealand *Carmichaelia* spp., only 8 out of 23 wild species are known to be "non-threatened", these are *C. odorata* Colenso ex Hook.f., *C. australis* R.Br, *C. glabrescens* (Petrie) Heenan, *C. monroi* Hook.f., *C. nana* (Benth.) Colenso ex Hook.f., *C. arborea* (G.Forst.) Druce, *C. petriei* Kirk, and *C. uniflora* Kirk. *Carmichaelia* are generally slow growing (Pollock, 1986). Herbivory is a major reason for their decline (Grüner & Norton 2006).

Carmichaelia odorata is a thicket-forming leguminous shrub found on river terraces, flats and streams and forest margins in New Zealand (Heenan 1996). *Carmichaelia arborea,* also a shrub (2 x 2 m), inhabits wetter South Island mountains (Heenan 1996). *Carmichaelia* increased foliar and biomass concentrations of coexisting plant species in glasshouse experiments (Bellingham et al. 2001). Removal of *Carmichaelia* by herbivory resulted in reduced N in the soil, reducing the N content of the remaining plants in the ecosystem (St. John et al. 2012). *Carmichaelia* seeds are long-lived and viability is high (Bellingham et al. 2001).

***Clianthus* spp**. (kakabeak) have distinctive beak-shape flowers and are typically colonisers of disturbed habitats such as landslips and riverbanks. Clianthus were cultivated by Māori and wild populations have persisted at sites where they were previously cultivated (de Lange 2022a). Both wild species, *Cl. maximus* Colenso and *Cl. puniceus* (G.Don) Sol. Ex Lindl., are at risk of extinction. Plants of the less disease-prone *Cl. maximus* were brought into commercial horticulture (sold as cv. Kaka King) and are widely available (de Lange 2022a).

Montigena consists of only one species, *Montigena novae-zelandia* (Hook.f.) Heenan or the "scree pea". This species is a long-lived, woody, rhizomatous subshrub found in restricted habitats in the eastern mountains of the South Island of New Zealand. The number of *Montigena* is declining and this species can be only found in the wild due to the difficultly associated with propagating it under artificial conditions (de Lange 2022b).

The genus ***Sophora*** (kōwhai) has eight species in New Zealand. *Sophora microphylla* Aiton (up to 25 m) and *S. tetraptera* J.Mill (up to 15 m) are the most widely distributed species and are frequently associated with open forests, and along forest margins (de Lange & Heenan 2006). *Sophora chathamica* Cockayne (up to 20 m*)*, grows on a wide range of soils in coastal Northland, Wellington and the Chatham Islands (Heenan et al. 2001). The other five species of kōwhai in New Zealand (*S. longicarinata* G.Simpson et J.S.Thomson, *S. fulvida* (Allan) Heenan et de Lange, *S. godleyi* Heenan et de Lange, *S. molloyi* Heenan et de Lange and *S. prostrata* Buchanan) occur in restricted habitats and tend to grow on sites that are harsh (i.e., rocky, infertile, calcareous, dry and/or windy). *Sophora microphylla* and *S. tetraptera* are tolerant of frost and drought and are easily established (Heenan et al. 2001). Kōwhai can tolerate partial shade but prefer full light (J. A. Wardle 2011). Kōwhai can be propagated directly from seed or cuttings and are easily transplanted (L. Nguyen et al. 2021).

Nitrogen fixation of nodulated kōwhai seedlings has been demonstrated using the acetylene reduction assay (T. D. Nguyen et al. 2017), but data describing N fixation rates and factors influencing N fixation is limited. Kim et al. (2017) demonstrated that the presence of earthworms improved the growth of rhizobia inoculated *S. microphylla* by influencing soil conditions (moisture, aeration, organic matter) (Kim et al. 2017).

The nectar of *S. microphylla* is toxic to honeybees causing a narcotic effect which can be fatal and have significant impacts on hives (Clinch et al. 1972). Kōwhai are not managed in New Zealand planted forests but their potential for commercial forestry is good based on their quality specialty timber and potential for plantation forestry (L. Nguyen et al. 2021). Nguyen et al. (2021) suggest that the residues could support a secondary industry such as a source of alkaloids for pharmaceutical applications. No research has been conducted on kōwhai silviculture (L. Nguyen et al. 2021) or their impact on *P. radiata* productivity in mixed plantings.

***Coriaria* spp.** (tutu) are woody, perennial actinorhizal plants. There are eight species of *Coriaria* endemic to New Zealand with *C. arborea* Linds. the largest (up to 8 m) and most widespread. *Coriaria sarmentosa* G.Forst (up to 1 m) is also common (Webb et al. 1990). The other endemic *Coriaria* spp., also nodulated, are rhizomatous and generally limited to high elevations (Silvester 1976). *Coriaria* can grow on a wide range of relatively infertile and dry sites including pumice, gravel and sandy soils (Newcomb & Pankhurst 1982).

The common occurrence of *C. arborea* as an understorey shrub in *P. radiata* plantations in New Zealand suggests its suitability for a mixed species system (Silvester 1976). Silvester (1976) observed increased height in early *P. radiata* growth planted near *C. arborea* on a bulldozed skid site in volcanic pumice soils in the central North Island. The large litter fall of *C. arborea* as well as its association with *P. radiata* mycorrhizal roots likely contributed to the N transfer (Silvester 1977). However, the vigorous growth of *Coriaria* may suppress recently planted *P. radiata* stands. On sites where N is not severely limiting, *C. arborea* is eventually shaded out by other shrub and tree species as stands mature. However, Silvester reports that following thinning, *C. arborea* may re-establish in the *P. radiata* stands, persisting if it receives at least 30 percent of full sunlight. *Coriaria* seed can germinate in the dark (albeit much slower than in light) but it is unknown whether they remain viable over long periods (Burrows 1995). An adjacent seed-supplying stand or direct seeding may be needed.

Coriaria arborea contributed 150 kg N ha^{-1} yr^{-1} over a 20-yr period to a floodplain in New Zealand (Silvester 1976) and 11 kg N ha^{-1} yr^{-1} as a 7 year old stand in a N depleted soil in South Westland, New Zealand (Menge & Hedin 2009). *C. arborea* is an obligate N-fixer and can maintain high rates of N fixation independent of soil N availability (Menge & Hedin 2009).

All parts of *C. arborea* are poisonous to animals and humans (Belcher & Morton 2013) and toxic honey can be produced under certain conditions if bees collect honeydew containing the phytotoxin tutin which is produced by the passion vine hopper when feeding on tutu (Robertson et al. 2010; Ministry for Primary Industries 2016). If *C. arborea* was to improve soil fertility in planted forests, the toxicity risk to humans and animals would need consideration.

***Discaria toumatou* Raoul** (matagouri or tumatakuru), an actinorhizal shrub, is found mainly in the South Island in short tussock grasslands, sand dunes and riverbeds (Thomas & Spurway 2001). In soils where P is not limiting, *D. toumatou* can grow up to 6 m high (Daly 1969). It is suppressed by weeds and has little tolerance for deep shade (Daly 1969). Root nodules of *D. toumatou* are efficient N-fixers (Morrison 1961). *Discaria toumatou* grows easily from seed (Keogh & Bannister 1992). Trees can be used for firewood and building material (R. Johnson 1961). The flowers produce good honey (Day et al. 1990).

Effects of N-fixing plants on planted forest soil fertility and productivity in New Zealand

Benefits to the long-term growth and productivity of *P. radiata* in New Zealand have been demonstrated conclusively for *Lupinus arboreus* in a coastal New Zealand forest, whereby N derived from *Lupinus arboreus* provided a means of storage and slow-release N (Figure 1) (Beets & Madgwick 1988) (see summary in Table 1, Supplemental Dataset S1). Unfortunately, lupin blight disease resulted in the decimation of *Lupinus arboreus* populations and the discontinuation of this as a N-fixing option for planted forests (Dick 1994).

Benefits to growth and productivity of *P. radiata* by *Lotus* species in New Zealand have been predominantly observational. *Lotus* spp. are very tolerant of low fertility soils, which are common to planted forests and have desirable traits which are highly amenable to forestry operations. However, despite previous plantings of *Lotus* in New Zealand planted forests (West et al. 1988; Monk et al. 2016) and existence of adventive *Lotus* spp. (Brockerhoff et al. 2003; Langer et al. 2008) there is limited data on N fixation rates and transfer/benefits to planted forests. Defoliation of *P. radiata* by a pest associated with lotus was an issue (Alma 1977) and is likely the reason that lotus plantings lost favour.

These past experiences with both lupin and lotus demonstrate that pests and diseases have been a major challenge to the use of N-fixing plants in New Zealand planted forests. Warmer temperatures induced by climate change are predicted in the future to provide ideal conditions for pest and diseases and therefore ongoing development of N-fixing species through plant breeding and pest and disease management strategies will be required if they are to be operationalised (Ferguson et al. 2019).

The early establishment trials proved that a variety of N-fixing plants and trees could tolerate low fertility soils and establish as an understorey or rotational crop in New Zealand planted forests. Persistence of the palatable N-fixing plants e.g., *Trifolium* spp., *Dorycinum* spp., *Ornithopus* spp. was generally poor due to grazing from pests (rabbits, deer, possums); or they grew slowly and were overcome by weeds (Gadgil et al. 1988). Approaches to reduce browsing by herbivores include using thorny and spiny plants (e.g., gorse) (Hanley et al. 2007), chemical characteristics such as toxins that influence palatability (A.M. Miller et al. 2006a), and associational refuge theory that suggests that unpalatable neighbouring plants can provide protection to focal plants from browsers, thereby reducing browsing (A. M. Miller et al. 2006b). If browsing and weed challenges could be addressed, these may be worth re-considering for N fixation options in New Zealand planted forests.

Known forest weeds in New Zealand such as broom (*Cytisus scoparius*) and gorse (*Ulex europaeus*) are N-fixing plants that readily occur in planted forests. However, they hinder forestry operations and can compete with *P. radiata* growth (as well as the growth of other beneficial plants) (Richardson et al. 1996). They may also provide benefits to *P. radiata* by increasing soil N but whether this outweighs the disbenefits requires further consideration (Watt, Clinton, et al. 2003).

Medicago sativa (lucerne), more suited to soils with low exchangeable Al, has been grown in association with *P. radiata* and N fixation was demonstrated (Goh et al. 1996); however, it was shown to decrease *P. radiata* growth in juvenile trees (Mead et al. 1993).

Nitrogen-fixing trees have not been assessed in New Zealand planted forests, possibly because the use of site resources by a less valuable crop has been considered a limitation. There is, however, a growing interest in the potential of using mixed species in plantation forestry for increasing productivity as well as having advantages in biodiversity, economy and forest health over monocultures (Liu et al. 2018). Opportunities beyond wood processing include using wood and forest residues to replace industrial fossil fuels and produce liquid biofuels such as biodiesel (P.W. Hall & Harnett 2020). According to a review by Marron and Epron (2019), mixed plantations containing N-fixing trees and non-fixing species show greater productivity (24% more on average) than monocultures of non-fixing species in temperate climates. Nitrogen-fixing trees can be more persistent than N-fixing herbaceous crops and could supply a continuous input of N throughout the whole rotation. More research is required to evaluate a N-fixing and non-N fixing mixed planted forest in a New Zealand context.

Acacia and *Alnus* spp. have been utilised overseas as an intercrop to improve soil N. Some of these species may be unsuitable due their high invasiveness (Bühlmann et al. 2014; Hiltbrunner et al. 2014; Watt et al. 2019). Spread risk must be assessed and N-fixing species must be managed to remain within forest boundaries. However, gene editing technologies, if approved in New Zealand, have the potential to revolutionise breeding programmes, possibly addressing the invasiveness of some species by providing trees that are infertile and unable to reproduce (Fritsche et al. 2018).

Native N-fixing species, such as *Sophora*, *Coriaria* and others may be suitable options. A recent review highlights the potential of *Sophora* spp. for commercial forestry (L. Nguyen et al. 2021). The role of *Coriaria* spp. as a source of fixed N in *P. radiata* forests in New Zealand has been observed (Silvester 1976; Silvester et al. 1979) although it has not been implemented operationally in planted forests. While there is increasing desire to introduce native trees and other plants actively into forests, there is much work to do to establish reliable methods for planting natives under a range of site conditions. Extremely limited knowledge is available on the potential role of native N-fixing plants in planted forests in New Zealand.

Planning for sustainable forest management

A key consideration that has emerged following the research carried out in the 1970s and 1980s is recognition of the impact of climate change on forestry systems. Pursuing N-fixing options that are tolerant to drier conditions will be important, particularly in drier areas that are predicted to become even drier (Watt et al. 2019). Negative impacts of N-fixing plants on *P. radiata* growth have been observed in dry or drought-prone sites (Balneaves 1982; Waring & Snowdon 1985; Smethurst et al. 1986; Mead et al. 1993; Nambiar & Sands 1993; Goh et al. 1996; Watt, Clinton, et al. 2003). Moisture levels are important for decomposition of the litter and roots and hence N availability (Beets & Madgwick 1988). Competition between the N-fixing trees and *P. radiata* may be managed by planting one crop earlier than the other (if early height growth is different), optimising N-fixing tree planting arrangement, pruning under water limiting conditions and by planting and maintaining only as many N-fixers as needed (Lavery et al. 2004). Selection of *P. radiata* genotypes more suited to competition can be used to reduce competition effects on *P. radiata* growth (Gautam et al. 2003; Ismael et al. 2022).

The use of N-fixing plants in low N environments is unlikely to result in increased off-site losses, such as nitrate leaching and nitrous gas emissions (Kou-Giesbrecht et al. 2021). However, the potential to cause N leaching by gorse, as well as plants with obligate N-fixing strategies has been highlighted (Mason et al. 2016; Menge et al. 2023). To ensure N losses to water bodies do not occur, it is critical to consider site-specific nutrient availability as well as different N-fixing strategies (Menge et al. 2014; Menge et al. 2015; Dovrat et al. 2020) along with *P. radiata* N requirements. Requirements for new N inputs versus internally recycled N can be variable at different sites, during a rotation and over time in a managed forest (Garrett et al. 2021).

An improved understanding of N cycling in planted forests (i.e., whole system N cycling) could provide opportunities to improve N transfer (Johnson & Turner 2019). Plants with low rates of N fixation, high leaf nutrient contents and high rates of nutrient cycling may be valuable components in the ecosystem (Forrester et al. 2005). Conversely, plants with high rates of N fixation may reduce whole system N cycling. For example, the presence of broom and lotus litter retarded breakdown of *P. radiata* pine litter and slowed the rate of N release in a microcosm experiment (Ganjegunte et al. 2005). Mycorrhizae are beneficial for legume establishment and growth, particularly in phosphorus-deficient soils (Nygren et al. 2012; Lazali & Drevon 2021). Further field studies are required to evaluate the impact of different understorey, including mycorrhizal associations, on decompositions and nutrient release. Evidence of N fixation in the absence of N-fixing plants (non-symbiotic or free-living N-fixation) has been demonstrated by red pine and pitch pine (average 50 kg ha^{-1} y^{-1}) (Bormann et al. 1993) and radiata pine (Stevenson 1959). Non-symbiotic N fixation is increasingly recognised as an important N provider in forests and should be considered in future work (Turner et al. 2019; Puri et al. 2020; Chalk et al. 2022). Nitrogen-fixing bacteria have been found in stem tissues of conifers and members of the Salicaceae family, including poplars (*Populus* spp.) and willows (Salix spp.) (Puri et al. 2020). Poplars and willows (*Salix* spp.) are fast-growing tree species which are a popular option for bioenergy, wood products and environmental services due to their high yields and ability to colonize nutrient-poor environments (Doty et al. 2016) and could be another option if their non-nodular N-fixing contributions were found to be sufficient. In New Zealand, N-fixing plants used in combination with alternative production tree species (other than *P. radiata*) is another knowledge gap.

There are many difficulties and uncertainties associated with the measurement of N fixation (Johnson & Turner 2019). Different approaches and methods were used to quantify N fixation rates (ranging from 40 – 230 kg N ha^{-1} yr^{-1}) reported in this review (see Supplemental Dataset S1) and as such can only offer comparison at a coarse level. Recent reviews discuss methods developed to estimate biological N fixation and provide a roadmap for the standardisation of N fixation research (Johnson & Turner 2019; Soper et al. 2021; Chalk et al. 2022). This roadmap can be used to design trials to understand interactions between N-fixing species and *P. radiata* and alternative production species under different soil fertility, climatic gradients, stand ages and densities.

More research is required to demonstrate predictable benefits to the productivity of New Zealand planted forests from the integration of N-fixing plants, to provide the confidence required to invest in this option (Table 2). Forest trials need to consider wider issues such as invasiveness and risk to biodiversity (including toxicity risks to humans and animals). Social research exploring public acceptability regarding the use of exotic and potentially invasive N-fixing plants is also required, as this will affect the range of species that can be considered for further research and potential operational use; the views of iwi should be given particular consideration due to the extent of forest land owned by them (Edwards et al. 2018). Technological improvements, such as plant breeding and adopting best practises for experimental trials, will enable the synthesis of existing and new knowledge into process-based models that can aid in selection of appropriate combinations of species matched to site conditions. Nitrogen-fixing plants, either alone or in combination with fertilisers (N & P) may offer returns through reductions of N fertiliser costs, yield increases and various ecosystem services. However, effects on ecosystem services such as weed suppression, pollinator attraction, erosion control, forage, increased biodiversity and improved carbon sequestration may be more difficult to quantify. Environmental costs associated with increased fertiliser use include nitrogen losses, fossil fuel consumption and CO_2 emission in

TABLE 2: Suggestions for important future research directions regarding the use of N-fixation to improve planted forest productivity in New Zealand.

Ecology of N-fixing plants in planted forests

- Re-evaluation of N-fixing plants that have previously been considered less suitable due to their requirement for intensive forest management. Trials to support knowledge gaps such as N-fixing rates of *Lotus* spp. at different levels of canopy cover and soil moisture, long-term assessment of N-fixing plants over a broader range of planted forest characteristics.
- Mixed species trials with N-fixing and non-N-fixing trees to understand interactions under a range of conditions relevant to New Zealand. Monitor and report on results using an ecosystem and social-ecological approach (which includes environmental, economic, ecosystem services and social aspects, see Yao et al. 2021).
- Trials to define the importance and potential of free-living N-fixing (non-symbiotic) microorganisms as a contributor to the fertility and productivity of New Zealand planted forests.
- Research to support understanding of opportunities for commercial kowhai forest industry.

Models and decision support tools

- Continued development of nutrient balance model (Smaill et al. 2011) to understand the N input required for increasing productivity and sustainability of planted forests and how N-fixing plants can contribute.
- Economic and carbon footprint assessment of N-fixing plants vs fertiliser in planted forests.
- Incorporation of N-fixing data into process-based models and decision support tools.
- Social research on acceptability of N-fixing plants in planted forests compared to fertilisers.
- Engagement with the forest management sector to facilitate a participatory approach and to ensure research targets practical options.

Plant breeding, nursery trials and biotechnology research

- Plant breeding of N-fixing cultivars for low fertility soils and future climate change scenarios (pest, disease and drought resistance with low fire risk).
- Plant biotechnology to develop N-fixing trees/plants that are unable to reproduce to prevent escape and risk to natural biodiversity.
- Research on native N-fixing plants, their N-fixing rates, factors that influence N-fixation and their potential for future planted forests.
- Manipulating the tree/forest microbiome to increase nutrient and carbon cycling and production of plant growth-promoting substances.

the manufacturing process as well as transport and application (Razon 2018). The Forest Investment Framework (FIF) is a modelling framework that includes assessment of some of the key ecosystem services provided by planted forests in New Zealand (Yao et al. 2021), but, at present, it does not include provision of N by N fixation. The development of process-based models such as CABALA (Battaglia et al. 2004) and decision-support tools that incorporate N fixation strategies can help forest managers and policy makers to improve the management of forest environment and resources.

Conclusions

This review summarises research into the use of N-fixing plants in New Zealand and in temperate regions in other countries, and the application of these to increase the productivity of planted forests in New Zealand. Much of this research was conducted in the 1970s to 1980s where several exotic N-fixing plants were shown to establish either with or under *P. radiata.* One long term trial demonstrated that N-fixing plants can provide benefits *to P. radiata* growth, but other trials showed that competition from the N-fixing plant had negative impacts on early growth of the targeted tree crop. Currently, there is limited understanding of how to successfully integrate N-fixing plants into planted forests to increase productivity and prevent negative impacts*.* Problems related to pests and disease as well as climate change issues, invasiveness and risk to New Zealand biodiversity need addressing before large-scale introduction of non-native N-fixing plants is used. New Zealand natives such as kōwhai (*Sophora* spp.) and tutu (*Coriaria* spp.) are options for intercropping; however, the conditions needed to establish and to provide N for the benefit of planted forests are unknown and there are issues around their toxicity that need to be addressed.

Despite these challenges, there are compelling reasons for using N fixation to increase soil N fertility for enhanced tree crop productivity. Biologically fixed N constitutes a valuable natural resource which, when managed properly, can be used for enhancing productivity or could at least complement or replace fertiliser N use and may ease the long-term pressure for increased productivity. Benefits include reduction of N fertiliser inputs (and the associated carbon footprint), minimising emissions to air, water and soil, and better opportunities for managing planted forests that maintain or improve biodiversity. With greater demands on forest soils (such as decreasing rotation length, increasing harvesting and climate change disturbance), it seems timely to re-consider the integration of N-fixing plants to improve planted forest productivity with a reduced environmental footprint. This approach, however, needs to be explored through well-funded research, integrated with forestry management practices, and delivered as practical options to ensure success.

List of abbreviations

N: nitrogen
N-fixing: nitrogen fixing
P: phosphorous
Al: aluminium
spp.: species
Ha: hectare
yr: year

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors contributed to the literature search, read and approved the final manuscript. LGG and SJS conceived and initiated the research, AN, KW and NMR conducted the literature review and drafted the manuscript, NMR, SJS and LGG revised the manuscript.

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Suppemental Data

Supplemental Dataset S1: Data obtained from N-fixing species grown in association with *Pinus radiata* in New Zealand and Australia.

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Supplementary Data

Data obtained from N-fixing species grown in association with *Pinus radiata* in Australia or the North Island (NI) or South Island (SI) of New Zealand (NZ).

Common name and species	Location	Trial length years (y); tree age; other comments	N-fixing species improved soil fertility*	N-fixing species improved *P. radiata* growth*	Method used to measure N-fixing rate*	Nitrogen fixed (kg N ha^{-1} yr^{-1})*	References
Clover *Trifolium* spp.	South Australia (34.6°S 150.4°E)	7y; juvenile; phosphorus (P) applied	Y	Y	N balance (soil above 7.5 cm)	96	Waring & Snowdon 1985
	West Coast, SI, NZ	3y; juvenile; P applied; results not suitable for statistical analysis	NM	IT	NM	NM	Fitzgerald 1981
	Kaingaroa and Mamaku Forests, Central NI, NZ	5-10y; over sowing trials	NM	NM	NM	NM	West et al. 1988
	Whakarewarewa, Central NI, NZ (38°11’S;176°16’E)	3y; mid-rotation	NM	NM	Acetylene reduction assay (relative quantification only)	IT	Gadgil et al. 1986; Gadgil et al. 1988
	Canterbury, SI, NZ (43°38’ S; 72°30’ E)	1y; juvenile; cut & carry (fixed N removed)	NM	NM	^{15}N dilution	71-134	Goh et al. 1996
Lotus *Lotus pedunculatus*	West Coast, SI, NZ	3y; juvenile; P applied; results not suitable for statistical analysis	NM	NM	NM	NM	Fitzgerald 1981
	Whakarewarewa, Central NI, NZ (38°11’S;176°16’E)	3y; mid-rotation;	NM	NM	Acetylene-reduction assay (relative quantification only)	IT	Gadgil et al. 1986; Gadgil et al. 1988
	Various forests, NI, NZ	5-10y; over-sowing trials	NM	NM	NM	NM	Brown 1988; Dale & Todd 1988; West et al. 1988; West et al. 1991
	Kaingaroa forest, Central NI, NZ	8y; juvenile – mid: P applied, grazed and ungrazed plots	NM	Y	NM	NM	West & Dean 1992
	Woodhill, NI, NZ (36°45’ S,174°26’E)	3y; juvenile	NM	NM	^{15}N dilution (above ground)	55	Wanjiku et al. 1997

Data obtained from N-fixing species grown in association with *Pinus radiata* in Australia or the North Island (NI) or South Island (SI) of New Zealand (NZ).

Common name and species	**Location**	**Trial length years (y); tree age; other comments**	**N-fixing species improved soil fertility***	**N-fixing species improved *P. radiata* growth***	**Method used to measure N-fixing rate***	**Nitrogen fixed (kg N ha^{-1} yr^{-1})***	**References**
Lucerne *Medicago sativa*	Canterbury, SI, NZ (43°38’ S; 72°30’ E)	2y; juvenile	NM	N	NM	-	Mead et al. 1993
	Canterbury, SI, NZ (43°38’ S; 72°30’ E)	1y; juvenile; cut & carry (fixed N removed)	NM	NM	^{15}N dilution	230	Goh et al. 1996
Lupin *Lupinus* spp.	Woodhill, NI, NZ (36°45’S,174°26’E)	2y; pre-planting	IT	NM	N balance (N content of ecosystem biomass components)	160	Gadgil 1971
	Woodhill, NI, NZ (36°45’S,174°26’E	8-11y; juvenile-mid; thinning & fertiliser treatments	NM	Y	NM	NM	Jackson et al. 1983
	Woodhill, NI, NZ (36°45’S,174°26’E	14y; mid-rotation; thinning & fertiliser treatments; post-lupin treatment	Y	N	N balance (N content of ecosystem biomass components)	80	Baker et al. 1986
	Woodhill, NI, NZ (36°45’S,174°26’E	17y; late-rotation post-lupin treatment N-mineralisation effects.	NM	Y	NM	NM	Beets & Madgwick 1988
	Whakarewarewa, Central NI, NZ (38°11’S;176°16’E)	3y; mid-rotation	NM	NM	Acetylene reduction assay (relative quantification only	IT	Gadgil et al. 1986; Gadgil et al. 1988
	Victoria, Australia	4y; juvenile; mean annual rainfall =800 mm)	Y	N	N balance (N content of roots & shoots)	37	Smethurst et al. 1986
	Western Victoria, Australia and southeast South Australia	4y; juvenile	Y	Y	NM	NM	Nambiar & Nethercott 1987
Broom *Cytisus scoparius*	Canterbury, SI, NZ (43°34’ S; 171°55’ E)	1y; juvenile; competition for water outweighed N benefits.	NM	N	^{15}N dilution (above ground)	111	Watt et al. 2003

Data obtained from N-fixing species grown in association with *Pinus radiata* in Australia or the North Island (NI) or South Island (SI) of New Zealand (NZ).

Common name and species	**Location**	**Trial length years (y); tree age; other comments**	**N-fixing species improved soil fertility***	**N-fixing species improved *P. radiata* growth***	**Method used to measure N-fixing rate***	**Nitrogen fixed (kg N ha^{-1} yr^{-1})***	**References**
Gorse *Ulex europaeus*	Canterbury SI, NZ (34°12’ S; 172°34’ E)	18y; gorse-control experiment	NM	N	NM	NM	Balneaves and McCord 1990
Acacia *Acacia* spp.	Victoria and Australian Capital Territory, Australia	7y; juvenile; various stocking rates	Y	N	N balance (N content of soil)	32	Turvey et al. 1983b
	Canberra, Australian Capital Territory, Australia (35°15’ S, 149°10’ E)	5y; juvenile; annual rainfall = 625mm	N	N	NM	NM	Forrester et al. 2007
Everlasting pea *Lathyrus latifolius*	Woodhill, NI, NZ (36°45’ S,174°26’E	3y; juvenile;	NM	NM	^{15}N dilution (above ground)	214	Wanjiku et al. 1997
Hairy Canary Clover *Dorycnium* spp.	Woodhill, NI, NZ (36°45’ S,174°26’E	3y; juvenile	NM	NM	^{15}N dilution (above ground)	71	Wanjiku et al. 1997
Serradella *Ornithopus spp.* **Crownvetch** *Coronilla varia* **Vetch** *Vicia spp.* **Tagasaste** *Cytisus palmensis*	Whakarewarewa, Central NI, NZ (38°11’S;176°16’E)	3y; mid-rotation; establishment trial	NM	NM	Acetylene reduction assay (relative quantification only	IT	Gadgil et al. 1986
Tutu *Coriaria arborea*	Central NI, NZ	0y; mid-rotation; observed increase in *P.radiata* tree height	N	IT (observation)	NM	NM	Silvester 1976

***Y = yes, N = No, NM = not measured, IT = inconclusive test**