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A review of legume research and extension in New Zealand (1990–2022)

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ABSTRACT

Legumes have underpinned transformational change on New Zealand sheep and beef farms over the last 30 years. This was through an emphasis on ewe nutrition based on lucerne or red clover dominant pastures, and increased use of subterranean and white clovers on uncultivatable hill country. Pre- and post-weaning lamb growth rates have increased, and enabled earlier slaughter of heavier lambs. The farm systems results include greater numbers of hoggets mated, higher lambing percentages and greater ewe efficiency (kg lamb weaned/kg ewe mated). Extension packages to support legume use have compared growth rates of resident and legume-based pastures, economic analyses of successful farms and management packages for the most appropriate legume in different environments. Over the same period, the dairy industry rapidly expanded in cow numbers and area onto flat irrigated land on the Canterbury Plains. The nitrogen deficiency of perennial ryegrass was overcome by a linear increase in nitrogen fertiliser use. Environmental concerns from this intensification has led to a legislated nitrogen cap of 190 kg/ha.year. This, coupled with a recent trebling in urea price, has returned attention to increasing the white clover content of these pastures. Nitrogen applications can be minimised by using diverse pastures sown with a legume, herb and <8 kg/ha of perennial ryegrass. Work on other legumes, including annuals and those with condensed tannins, has to date failed to increase their use in most pastoral settings, with the exception of the perennial lupin which is adapted to high-aluminium soils in the South Island High Country.

Keywords: alfalfa, *Lupinus polyphyllus* L, *Medicago sativa* L, red clover, rhizobia, subterranean clover, *T. michelianum* L, *T. pratense* L, *T. repens* L, *T. subterraneum* L, *T. vesiculosum* L, technology transfer, *Trifolium ambiguum* M. Bieb, white clover.

Introduction

Legumes have always played a central role in New Zealand's pastoral-based agriculture systems (Caradus *et al.* 2021). Arguably, the country's wealth has been generated by the ability of white clover (*Trifolium repens* L.) to fix nitrogen (N) from the atmosphere, which is then transferred, predominantly via animals, to the associated perennial ryegrass (*Lolium perenne* L.) plants (Caradus *et al.* 1995). Indeed in the late 1980s white clover was considered so important that it was named as New Zealand's 'competitive edge' and a special symposium was held to celebrate that fact (Woodfield 1995). It remains the most commonly sown legume, and is supported by the breeding of new cultivars by commercial companies and the local herbage seed industry. The feed value of white clover and its contribution to New Zealand milk and meat production are well documented (Brock *et al.* 1989) and taught to undergraduates early in their academic career. White clover has the ability to produce clonal daughter plants from stolons and regenerate from a hard seed bank (Knowles *et al.* 2003). This ensures it is the legume uppermost in people's minds when they generically refer to it being a 'good' or 'bad' year for clover from Southland to Northland. In the last 30 years much of the publicly-funded breeding effort for white clover has had a molecular focus (e.g. Jones *et al.* 2006) but so far this has failed to transfer to commercially successful outcomes. Alongside this superstar of the New Zealand pastoral sector, other legumes have received less historic research attention and advocacy. Red clover (*Trifolium pratense* L.) is often included in pasture mixes in 'summer safe' regions, defined as those expected to receive sufficient summer rainfall to support pasture growth in most years. In contrast, lucerne (alfalfa; *Medicago sativa* L.) and subterranean (sub) clover (*Trifolium subterraneum* L.) are promoted for eastern dryland regions (350–800 mm rainfall) that do not have access to irrigation, and experience 1–5 months of water-stress-induced yield reductions in most years. These four legumes have received the bulk of the research and extension messages over the last 30 years. They are the most sown species across the diverse soil types and climates that make up the New Zealand landscape.

To understand the role of these legumes in New Zealand pastures, it is also important to understand the changes in land use that have driven the research and extension agenda. Traditionally, dairy farming occurred in regions considered 'summer safe', such as Waikato and Taranaki, which received >1000 mm of rainfall annually. However, since the 1990s, the introduction of centre pivot irrigation onto the previously summer dry (650 mm annual rainfall) Canterbury Plains led to rapid expansion of dairying farming. The result was that urea fertiliser replaced N fixation to support high stocking rates (3.44 cow/ha cf. national average of 2.86; LIC and DairyNZ 2021) on shallow soils that are prone to nitrate (NO_3^-) leaching (Carrick *et al.* 2013).

The increase of 2.7 M dairy cattle (including bobby calves) to the national herd between 1990 and 2021 (Statistics New Zealand 2022) also led to expansion of dairy support land for grazing replacement stock and growing winter forage crops. The pastoral land under dairy increased from 1.4 to 2.2 Mha from 1990 to 2020/21. This was associated with a reduction in the number of sheep and beef farms from 19 600 to 9165 (Beef + Lamb New Zealand Economic Service, Statistics New Zealand 2022) as land was converted to dairy and the remaining farms increased in size. The aim of this paper is to explain how these changes in land use have driven the legume research and extension that has occurred in New Zealand over the last 30 years. It will outline the impact of the dairy expansion on the sheep and beef sector, the importance of legumes to cope with that change and the impact of those changes on productivity. It will also highlight how recent legislative change, that limits inorganic N to 190 kg/ha, is likely to impact on farms and the current research strategies required to work within that limit. The objective is to show how legumes (genotype; G) have played a central role in a range of livestock farming systems (environments; E) provided appropriate management (M) packages are available and implemented on-farm. Thus, it will explore legume research and use in New Zealand through the interaction of G × E × M.

Nitrogen and the dairy industry

At a global level the importance of N fertiliser to ensure the population is fed has been summarised succinctly by Evans (1998) and van Ittersum (2011). Essentially, until the 1960s, expanding the area of arable land was necessary to feed a growing global population. However, the arrival of inorganic N fertiliser as part of the 'green revolution' enhanced crop production and increased yields through agricultural intensification. This essentially stopped forest clearing for food production for the next 50 years. The tool of using inorganic N only arrived in New Zealand in the 1990s. Until that time white clover had been the main source of N inputs into predominantly pastoral-based farming systems. Furthermore, the main area of cropping land on the Canterbury Plains used crop rotations. These had a regenerative pasture or white clover seed crop phase followed by depletive crops such as wheat and barley before returning to legume crops or the pasture phase to restore the soil N levels for the following cereal crops (Addiscott 2005). This practice remains in place for many of the cropping areas on deeper soils. However, the Canterbury Plains also has 53%, or 890 000 ha, of shallow stony soils (soil < 0.45 m, slope < 15°; Carrick *et al.* 2013) that are difficult to crop. This plain is also the largest area of flat land in the country, sitting over abundant water in unconfined aquifers. In the 1990s, this land was transformed by the arrival of centre pivot irrigation. The application of water highlighted that N was actually more limiting for pasture production. Mills *et al.* (2006) reported that a typical dryland (rainfed) pasture grew 6.5 t dry matter (DM)/ha.year. Full irrigation only increased that yield to 10 t DM/ha/year (Fig. 1). It was only with the addition of N fertiliser that the maximum potential yield of >20 t DM/ha.year could be achieved. Therefore, it is not surprising that the use of inorganic N increased linearly through the 1990s as the irrigated dairy conversions continued (Moot *et al.* 2020*a*). Based on the assumption that fully fertilised grasses need a leaf N content of about ~3.5% (Peri *et al.* 2003) to maximise light interception and photosynthesis, there is a need for ~700 kg N/ha to meet demand. Assuming about 200 kg N/ha is mineralised, based on the yield of the non-fertilised plots, another 500 kg N is required. If we assume that N is fixed at ~25 kg N/tonne of legume grown (Lucas *et al.* 2010; Peoples *et al.* 2012), and these pastures contain ~20% legumes over the year, that provides another 100 kg N/ha. The shortfall is then ~400 kg N/ha.year. Farmers in Canterbury and other dairy areas of New Zealand increased their N use accordingly (Fig. 2), particularly with the arrival of the clover root weevil (*Sitona obsoletus* Gmelin), which reduced the N fixation component (Eerens *et al.* 2005). The consequent increase in stocking rates led to increased milk production, which increased land values and locked in the need for high levels of inorganic N. The public backlash against this dairy expansion was galvanised

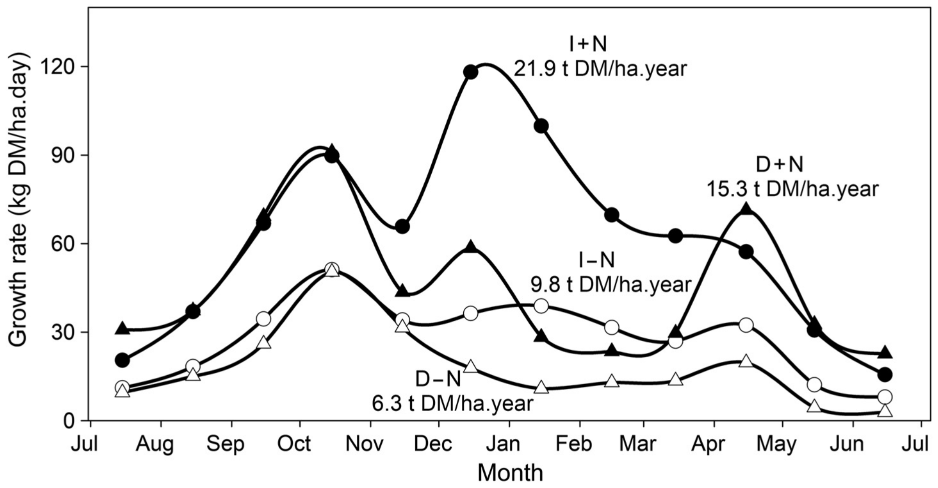

Fig. 1. Mean daily growth rate (kg DM/ha.day) and annual production (t DM/ha.year) of a dryland 9-year-old 'Wana' cocksfoot monoculture averaged over two growth seasons at Lincoln University, New Zealand. Treatments were fully irrigated with non-limiting N (I + N; ●), fully irrigated with no N (I − N; ○), rainfed with non-limiting N (D + N; ▲) and rainfed with no N (D − N; △) (Mills *et al.* 2006; Mills *et al.* 2009).

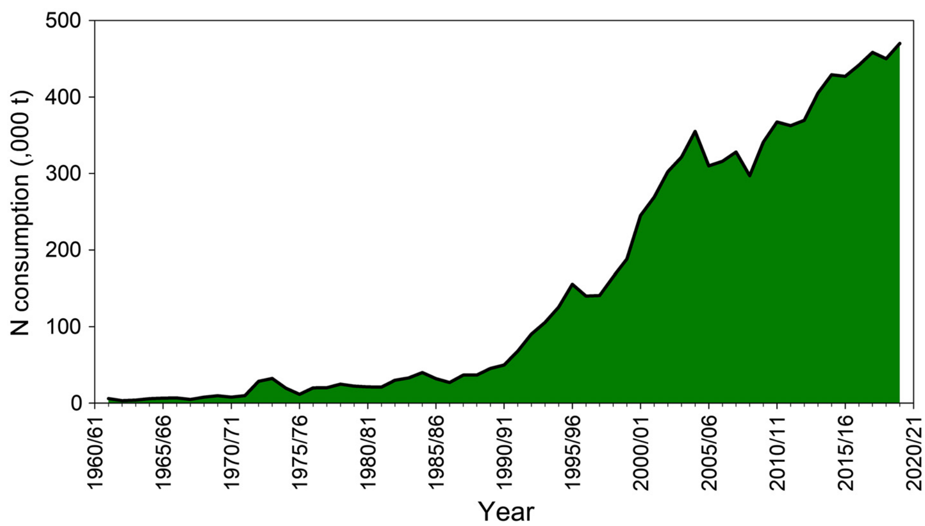

Fig. 2. Total nitrogen (N) consumption (x000 t) in New Zealand. Data sourced from the New Zealand Fertiliser Association (https://www.fertiliser.org.nz/) to 2017-18. Data for 2019 were sourced from the International Fertiliser Association IFASTAT database (https://www.ifastat.org/databases/).

by predicted increasing levels of NO_3^- in ground water and streams (Dymond *et al.* 2013), particularly caused by winter leaching from urine patches on stony soils (Di and Cameron 2002). The resultant legislative change in 2021 has now restricted the amount of N allowable to 190 kg N/ha (https://www.legislation.govt.nz/regulation/public/2020/0174/latest/LMS364253.html). This reduction aims to reduce pasture production but also nitrous oxide (N_2O) losses from the use of urea (van der Weerden *et al.* 2016).

Research to mitigate the impact of NO_3^- leaching has concentrated on reducing the N output from cows through inclusion of plantain (*Plantago lanceolata* L.) (Minnée *et al.* 2020; Navarrete *et al.* 2022) and chicory (*Cichorium intybus* L.) (Mangwe and Bryant 2021), while trying to find pastures that can support milk production without the need for high inorganic N inputs. To this end, Myint *et al.* (2021) evaluated monocultures, binary and tertiary mixes of perennial ryegrass, white clover and plantain under irrigated conditions. They identified the optimal mix as 12 kg/ha perennial ryegrass plus 7 kg/ha of white clover and reported this mix was just as productive as the same pasture with the addition of ∼200 kg N/ha, with both

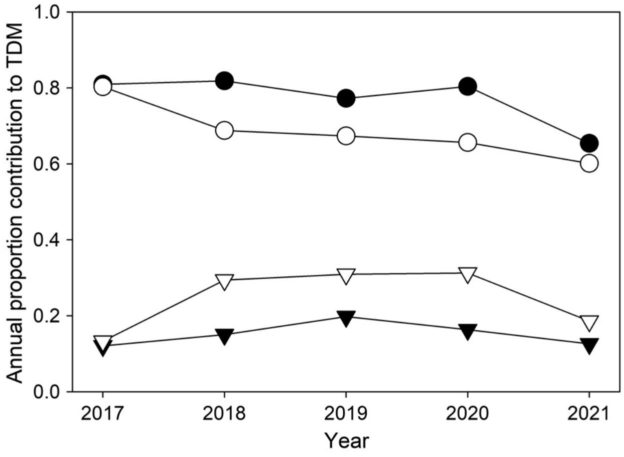

Fig. 3. Annual proportion of perennial ryegrass (circles) and white clover (triangles) components of an irrigated 50:50 perennial ryegrass/white clover pasture mix with (closed) or without (open) nitrogen fertiliser over 5 years at Lincoln University, Canterbury, New Zealand from the diversity experiment described in Myint *et al.* (2021).

pastures producing 20.5 t DM/ha.year. However, the N drove changes in botanical composition over time with higher grass and less legume present (Fig. 3). Further research, with all possible combinations of six pasture species, identified a four-species mix, sown with 7.5 kg/ha perennial ryegrass, 5.6 kg/ha plantain, 1.9 kg/ha white clover and 4.4 kg/ha red clover, as the optimal combination to maintain diversity and productivity under irrigated conditions (Black *et al.* 2021). This pasture mix produced and yielded 17.4 t DM/ha.year with no applied N. This result confirms previous research (Hurst *et al.* 2000; Black *et al.* 2006*a*) that has also advocated a 4–8 kg/ha ryegrass sowing rate to ensure legumes are established at a level that can support up to 40% legume to optimise production (Cosgrove 2005) without the need for inorganic N.

Legumes for sheep and beef systems

The impact of N for dryland (rainfed) systems was also shown by Mills *et al.* (2006). The addition of N increased pasture yields from 6.3 to 15.3 t DM/ha.year. This highlighted that N deficiency was also the main limitation to rainfed systems. Obtaining that N from the most appropriate legume (G) has been the focus of research and extension for the last 30 years, which has contributed to productivity gains in the sheep and beef systems.

Lucerne

The initial focus on lucerne for summer dry east coast environments confirmed the seasonal nature of plant partitioning (Moot *et al.* 2003). Understanding the physiological responses of lucerne to environmental cues (temperature and photoperiod) has enabled best grazing management practice to be developed and implemented on-farm (Avery *et al.* 2008). Subsequent adoption of management practice based on plant growth rather than phenological stage (e.g. flowering; Sheaffer *et al.* 1988) has continued to be reported (Anderson *et al.* 2014) and refined for different stock classes (Moot *et al.* 2016), including for beef cattle in Argentina (Berone *et al.* 2020). These research results have created impact through a Beef + Lamb New Zealand (B + LNZ)-maintained lucerne text alert extension service received by over 1300 users. As the area of lucerne on individual farms has increased, further research examined how some set-stocking could be accommodated at lambing (Sim and Moot 2019), before rotational grazing with mobs of up to 700 ewes plus lambs after ~4 weeks. The improvement of animal performance was detailed for 'Bog Roy', a high country station (350 mm annual rainfall) over an 11-year period (Moot *et al.* 2019). This demonstrated the impact of the increased lucerne area from 30 to 200 ha and the subsequent economic improvements. Specifically, the total lamb weight weaned increased from 90 to 160 t, initially through improved condition score and lambing percentages of the ewes from 110% to 135%. Mean daily lamb live-weight gain increased from 170 to 220 g/hd.day, which enabled earlier weaning at 85 compared with 120 days. Consequently, the ewes did not lose as much condition during lactation, so they required less feed to return them to mating weight, and the total lamb weaned per ewe mated increased from 26 to 36 kg.

Despite the documented success of several high profile farmers in adopting more direct feeding of lucerne there is always some hesitation to change. Therefore, a recent Hill Country Futures research programme (https://www.hillcountryfutures.co.nz/) has documented the yield advantages of lucerne and other improved species compared with the resident vegetation. Fig. 4 shows that, over 3 years on a summer dry Banks Peninsula property, lucerne consistently grew 2–3 times as much feed as the resident pasture (Smith *et al.* 2022). This occurred in both a summer drought year (2020–21) and a wet summer year (2021–22), which highlights the increased resilience to the variability of climate that the legume has provided, because it is never deficient in N. In this case the lucerne is used for grazing hoggets that are lambing to ensure these young stock are not underfed during lactation, when they still need to grow themselves. Thus, the appropriate management package (M) coupled with documented case studies of the right species (G) in the right environment (E) has been instrumental in driving practice change on-farm (e.g. Tayler *et al.* 2016). To integrate lucerne on-farm also requires understanding of the animal issues that may cause reluctance for on-farm integration. One area of concern is high levels of coumesterol in lucerne herbage that can cause premature mammary development (Fields *et al.* 2016) and reduce ovulation rates. High coumesterol levels (>25 mg/kg DM) have been shown to be

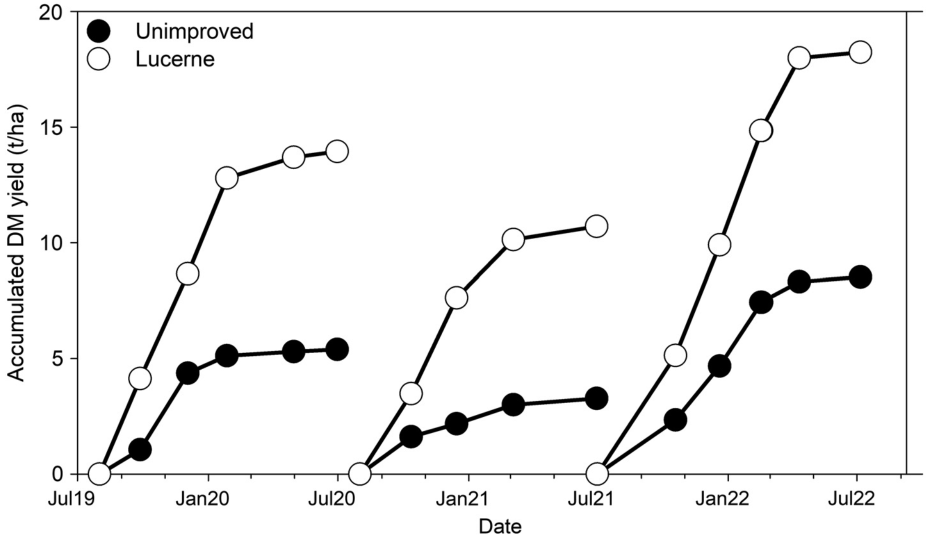

Fig. 4. Total accumulated dry matter (DM) production (t DM/ha) of improved and unimproved pastures over three growth seasons at Willesden Farm, Banks Peninsula, Canterbury (Smith *et al.* 2022). Annual (July–June) rainfall was 718 (2019–20), 629 (2020–21) and 768 mm (2021–22).

caused by high humidity within the canopy and independent of plant growth stage (Fields *et al.* 2018). Removing ewes 2–3 weeks before mating has been determined as adequate to reduce the potential for lowered conception (Fields *et al.* 2019).

The ability to encourage on-farm adoption has required continuous high quality research to underpin the extension process (Carberry 2001). For lucerne that work has focussed on using 20 years of research to update the APSIM_Lucerne model with particular emphasis on understanding the impact of fall dormancy and grazing management on lucerne quality (Ta *et al.* 2020) growth and development (Yang *et al.* 2021, 2022). In addition, a simplified yield calculator based on thermal time has been developed to enable farmers in other regions to use local weather records to estimate yield (Moot *et al.* 2022).

An ongoing debate related to the use of lucerne monocultures is whether the inclusion of a grass can improve the yield and quality of feed. In a 5-year grazing experiment on a shallow soil at Ashley Dene in Canterbury, Moot *et al.* (2020*b*) confirmed that live-weight gain of lambs was directly proportional to the amount of lucerne in the diet. The animal production from the lucerne–grass mixes was not different to the monoculture in the first year or two, when the lucerne dominated the pastures. However, once the grass component increased, the overall quality of herbage declined and so did animal production. A feature of this grazing experiment was the ceiling growth rate of ~320 g/hd.day achieved by the Coopworth lambs stocked at 14 ewes plus twins/ha. Lamb growth rates were buffered by ewe live-weight so the impact of the lower legume content was only obvious when the total live-weight of the systems was considered. Recent interest in multispecies mixes that include lucerne in these dry areas has again posed the question about using monocultures. This is currently being addressed in a new farmlet study on low and high P soils at Lincoln University (https://drylandpastures.com/research-projects/regenerative-agriculture-dryland-experiment-rade/).

Red clover

One of the advantages of monocultures is that they are able to target weeds effectively, which can overcome some of the difficulties associated with legume establishment in hill country (Tozer and Douglas 2016). This strategy has been used to successfully integrate red clover monocultures into satellite areas of hill country farms in wetter (800–1100 mm) environments (E). In this case the right plant (G) is not lucerne, except on free-draining sandy soils. For example, Chapman *et al.* (2021) reported that their previous pastures were browntop (*Agrostis capillaris* L.) dominant and produced ~4 t DM/ha. The addition of superphosphate and oversowing with white clover increased this to ~6 t DM/ha but did not alleviate the lack of spring (lactation) feed that was the major issue limiting stock performance on the farm. The easily cultivatable free-draining light land had been put into lucerne or was essential to grow forage crops to feed off during the long (110+ day) winter. Thus, they investigated the impact of introducing red clover dominant pastures into their system. The spring growth rates of the legume rich pastures were 80 kg DM/ha.day compared with the grass at 44 kg DM/ha.day despite the addition of 40 kg N/ha. The resident vegetation was only producing 9 kg DM/ha.day over the same period. During the initial 3–4 years of legumes, the grass weeds (browntop) and red fescue (*Festuca rubra* L.) could be controlled with selective herbicides. This also enabled other high quality forage species such as plantain to be included with the legumes. In this situation, legume rich pastures growing 16 t DM/ha.year are also fixing large amounts of N that is available to following grasses. When Italian ryegrass (*Lolium multiflorum*) was oversown in Year 3 into the red clover dominant pasture, the total annual yield was 30 t DM/ha with no N fertiliser applied. At Inverary Station, the impact of system change was evident in the increased scanning percentage (from 150% to 170%) and decreased lamb wastage (from 25% to 15%). The difficulty with red clover remains its lack of longevity (Brown *et al.* 2005), despite efforts to increase persistence (Ford and Barrett 2011), so identifying which grass to sow into it after the weed grasses have been eliminated is the next challenge. The prime candidate in this environment is timothy (*Phleum pratense* L.), which fits with rotational grazing that is required to maintain red clover. This combination of species (G) has been long advocated for these summer cool moist environments, but usually for conserving as hay. Thus, renewed focus on the management (M) practices was required to ensure they could be successfully maintained.

Subterranean (sub) clover

Subterranean clover use in New Zealand is usually as part of a grass-based pasture rather than sown as a monoculture. However, it remains a minor legume despite its obvious benefits in summer dry east coast regions (Costello and Costello 2003; Grigg *et al.* 2008) and extensive efforts to detail the key management periods to encourage its survival on-farm (Olykan *et al.* 2019). Much recent subterranean clover research in New Zealand has focussed on determining whether ratings for flowering dates, hardseededness (Teixeira *et al.* 2020*a*) and other traits documented from Australian breeding programmes, are consistent in temperate New Zealand (G × E). A meta-analysis of subterranean clover flowering dates showed that cultivars could be grouped into either 'early' or 'late' genotypes. Specifically, the time of autumn break had little impact on the date of spring flowering. This was driven by thermal time accumulation. Early cultivars required ~800 degree-days from the shortest day to flower while late cultivars took ~1100 degree-days. The longer spring growth is more appropriate for New Zealand conditions, where winter soil moisture has usually been recharged. However, recommendations remain to include several cultivars in a mix (Lucas *et al.* 2015) to allow the most adapted cultivar to dominate over time. To aid the management of subterranean clover, Guo *et al.* (2022) predicted the time of key development stages for early and late flowering cultivars across New Zealand. They mapped how the time of opening rain affected the time to first grazing using a 30-year weather dataset. This can affect the time of herbicide application, which should be based on the number of leaves present (Lewis *et al.* 2017). They also examined the time when flowering can be expected in different parts of the country, being mid-August for late flowering cultivars in the North Island and mid-September to mid-October in the South Island. The period of safe grazing, between the fourth trifoliate leaf and flowering, was considered to be 25% longer for 'late' than 'early' cultivars but this will change with soil type. In some situations the niche occupied by subterranean clover may also be occupied by white clover (Olykan *et al.* 2022), but management should focus on the subterranean clover to increase the content of the earlier growing legume (Olykan *et al.* 2021) to maximise pre-weaning live-weight gain in summer dry environments. Indeed cocksfoot (*Dactylis glomerata* L.) based pastures that included subterranean clover persisted for >8 years with the clover content dependent on the previous seasons seed set and the time of opening rain in autumn (Mills *et al.* 2015; Taylor *et al.* 2021). There is opportunity to further exploit subterranean clover, particularly in saturated spring soil conditions, where the *yannicum* sub-species appears more suited than the commonly used *subteraneaum* (Taylor 2019). Under cold stress in New Zealand winters, some cultivars have shown leaf reddening due to anthocyanin in the leaves, but this is largely cosmetic in nature and has not affected yield (Teixeira *et al.* 2020*b*).

Other legumes

These four main legumes have been advocated in New Zealand for at least 50 years. However, the development of specific management practices for each legume coincided with the need for intensification of hill country regions, including through helicropping (aerial direct drilling) (Lane *et al.* 2016), forced by the dairy expansion. Other legumes have also been tried and some have been valuable to farmers in specific niche areas, but remain minor in total seed sales (Monk *et al.* 2016) and thus receive little commercial support for their development. These include Caucasian clover (*Trifolium ambiguum* M. Bieb.) for which nodulation (Pryor *et al.* 1998; Black *et al.* 2014*a*) and establishment difficulties (Black *et al.* 2006*b*) have been overcome; however, it has failed commercially because it is difficult to produce high seed yields from. This means the value chain for seed growers and commercial companies is limited (Monk *et al.* 2016). Efforts to hybridise it with white clover (Widdup *et al.* 2003) have not yet produced a New Zealand bred cultivar, and Caucasian clover seed is no longer available commercially. In contrast, balansa clover (*Trifolium michelianum* L.) is a prolific seeding species (Nori *et al.* 2019) with several cultivars available. It has been shown to contribute to the total legume content in a mixed sward if managed appropriately (Monks *et al.* 2008; Mills *et al.* 2015). However, it has proven difficult to maintain and regeneration can be inhibited by hard seed or high soil temperatures (Olykan *et al.* 2021). Balansa clover has shown high total dry matter yields and early spring growth due to a high radiation use efficiency compared with other winter annuals (Nori *et al.* 2015*a*). The need to allow reseeding is difficult to manage in mixed pastures (Macfarlane *et al.* 2015). Reseeding has also been an issue for arrowleaf clover (*Trifolium vesiculosum* L.), with the highest hard seed content (Nori *et al.* 2019) meaning it does not fit easily into New Zealand's grazed pasture-based farm systems. It is also later to produce feed than sub and balansa clovers, so it is less useful during early lactation when the quantity and quality of feed is most important to support lactating stock. In contrast, gland clover (*Trifolium glanduliferum* Boiss.) is the earliest flowering of these annuals (Nori *et al.* 2015*b*), but seeds before it has taken full advantage of the spring moisture conditions. Thus, its environment of opportunity appears limited to dry faces in low (~350 mm) rainfall environments. Soft-seeded Persian clover (*Trifolium resupinatum* L.) can result in all seed germinating in late spring after seed set, with subsequent seedling death in the summer dry period. This means that no seed is set for regeneration (Nori *et al.* 2019), but it can be used as a one-off specialist crop. There are genotypes with greater hardseedness that may be more appropriate (Snowball 1993). At this stage, all of these species have limitations as one or more of the G × E × M components required to make them viable options for on-farm adoption requires further development.

Russell lupin

One legume, the perennial Russell lupin (*Lupinus polyphyllus* Lindl.), has found a value chain in a specific environment. Lupin seed is produced in Canterbury for export into the US ornamental home garden market. Thus, seed is available for purchase, so availability is not the issue that it is for Caucasian clover. Both of these species have been advocated for a low pH, high soil aluminium niche for several decades (Scott 2001). However, the utility of the perennial lupin was questioned in relation to animals actually grazing it and the subsequent production that could be expected (Scott 2014). An on-farm comparison of lucerne and lupins developed a management package to utilise the species (Black *et al.* 2014*b*, 2015; Black and Ryan-Salter 2016) for merinos in this environment. It has been sown with cocksfoot and Caucasian clover as companion species on previously undeveloped browntop dominant intermontane regions. Its use as a pastoral species is questioned by environmentalists who have concerns about its impact on birds in braided river systems (Scott 1989), so the management requires consideration of where to sow and when to graze to eliminate any potential spread outside of the paddock area. The advantage of the perennial lupin is that its *Bradyrhizobium* survive the hostile soil environment by living in root calluses and thus it can continue to fix N when more sensitive species have died (Ryan-Salter *et al.* 2014; Berenji *et al.* 2017).

Condensed tannins

There has also been considerable research attention on the use of legumes with condensed tannins (CT) to improve livestock performance. *Lotus corniculatus* L. has been shown to increase wool production and ewe efficiency (Barry *et al.* 1999), and also reduce faecal parasite egg counts and increase lambing and weaning percentage (Barry *et al.* 2003). *Lotus pedunculatus* Cav., sulla (*Hedysarum coronarium* L.) and sainfoin (*Onobrychis vicifolia* Scop.) reduced egg hatching as the concentration of CT was increased (Molan *et al.* 1999). Furthermore, *Lotus* spp. continue to be advocated for improving productivity of low pH, high aluminium soils (e.g. Stevens *et al.* 2020) but their niche opportunity is often thwarted by inconsistent seed supply (Monk *et al.* 2016) and difficulties of establishment in extensive high country terrain, under a predominantly set-stocked management (Berenji *et al.* 2018). Dairy research on *L. corniculatus* has demonstrated increased milk yields and feed conversion efficiency compared with ryegrass and white clover pastures (Harris *et al.* 1998) but to date the challenges of maintaining it in a dairy rotation have prevented adoption. The most effective method may be to use *Lotus* spp. as silage to overcome periods of feed deficit (Woodward *et al.* 2002). Overall legumes that contain CT have shown promise in many research environments but have not yet been integrated into farm systems. Consequently, the research activity on these legumes has declined over the last 30 years. It may be revised as a tool to mitigate climate change, with results showing the potential to use legumes with CT to reduce methane (CH_4) emissions (Waghorn *et al.* 2002).

Rhizobia

In most cases the rhizobia required for symbiotic N fixation are considered present in the New Zealand soils (Lowther and Kerr 2011). This is the case for white, red and sub clovers for which the addition of rhizobia is considered unnecessary unless new land that has not previously been in pastures is being broken in. The ubiquitous nature of the standard TA1 strain has been confirmed through investigation of nodule occupancy from many different locations and soil conditions (Shah 2019). These rhizobia seem to be equally successful for nodulating balansa, Persian and gland clovers. New techniques have confirmed that any rhizobia added with white clover seed are quickly lost from the nodule and the resident population invades (Wigley *et al.* 2016*a*). For lucerne, the introduced rhizobia were found for several months after sowing (Wigley *et al.* 2016*b*), although other bacteria have also been shown to form nodules, even in the absence of rhizobia (Wigley *et al.* 2017). The success of lucerne establishment was largely independent of the seed coat used but inoculation increased yield by 40% in the first year until the rhizobia infected the uninoculated control (Jáuregui *et al.* 2019). In drier environments, a coated seed coat was most effective at ensuring nodule occupancy of the desired rhizobia strain (Wigley *et al.* 2015). The search for rhizobia with tolerance to different pH conditions (Shah *et al.* 2021, 2022), or those that can fix N and solubilise phosphorus has shown some success in the laboratory (Seth 2017) with work in progress to translate these results into the field.

For other legume species, specific rhizobia are required and their absence can be a cause of establishment failure. Black *et al.* (2014*a*) showed that the slow establishment of Caucasian clover could mean the bacteria are dead before the roots are sufficiently developed to be invaded and the symbiosis established. They transplanted low-vigour plants from a high country station to warmer conditions and saw an immediate recovery and root nodulation. This issue remains to be resolved if Caucasian clover is to become successful in this environment, despite the selection and commercialisation of rhizobia specifically for this legume (Pryor *et al.* 1998). There is evidence that rhizobia from Caucasian clover are more tolerant of low pH/high aluminium soils than lucerne (Berenji *et al.* 2017). The impact of inoculation may not always be apparent immediately after sowing. In cultivated soils the release of N may be sufficient to grow the establishing seedlings, so the benefits of inocula tion are not immediately obvious. However, in the second season, once the soil N has been depleted, inoculated plants have been shown to out-yield non-inoculated plants (Berenji *et al.* 2015).

Impact on greenhouse gas emissions

It is difficult to quantify the exact impact of legumes on the sheep and beef sector over the last 30 years. However, the area of farmed land has reduced by 38% or 4.6 Mha (Fig. 5). Over the same period, total sheep numbers have declined from 57.9 M to 26.0 M, and the number of breeding ewes from 40.4 M to 16.6 M between 1990–91 and 2020–21 (Fig. 6). Conversely, increased lambing percentages (from 100% to 132%) and higher lamb growth rates (Moot and Davison 2021) have meant corresponding total lamb production has only dropped by 5–10%. Over the same period the total greenhouse gas emissions from CH_4 and N_2O, expressed as CO_2-equivalents (CO_2-e) have dropped by about 30% (Fig. 7) because of the decline in animal numbers. In addition, the emissions intensity (kg methane/kg carcass weight) has declined by 30% from 1 to 0.7 kg from 1990 to 2016 (Ledgard 2017). This is because ewes are heavier and more efficient at raising lambs. There has also been an increase in hogget mating which can only occur with ewe lamb target weights of 48–55 kg/hd (Haslin *et al.* 2022) if animals are growing 220+ g/hd.day from birth (~5 kg) to mating. Thus, a range of legumes suited to different parts of New Zealand have contributed to the transformation of the sheep and beef industry.

Despite this, the emissions profile of New Zealand remains a challenge for agriculture. Over 80% of the country's electricity is produced from renewable sources, and so pastoral-based agriculture is responsible for over 50% of

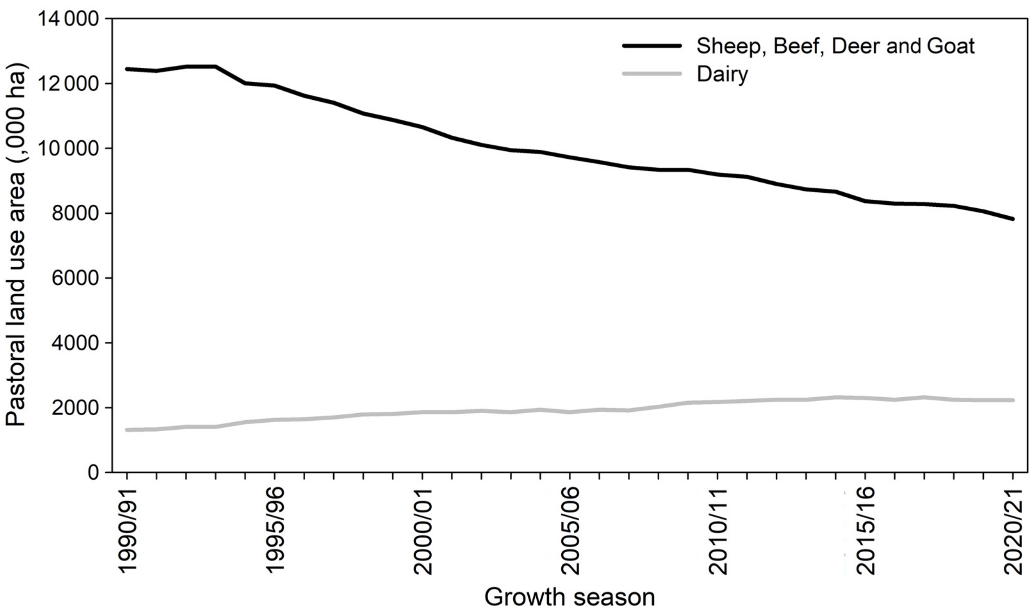

Fig. 5. Change in pastoral land area for sheep, beef, deer and goat (—) and dairy (—) farming systems in New Zealand from 1990–91 to 2020–21. Figures for 2020–21 are provisional. (Note: This figure was produced from data supplied by the Beef + Lamb New Zealand Economic Service and includes Stats NZ's data, which are licenced by Stats NZ for reuse under the Creative Commons Attribution 4.0 International licence.)

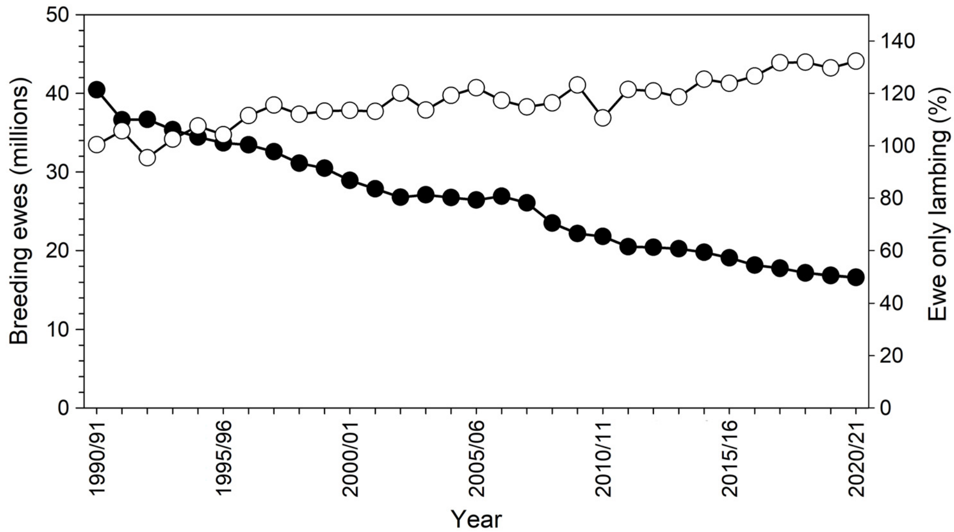

Fig. 6. Change in the total number of breeding ewes (2 tooth and over put to ram; ●) and ewe lambing percentage (○) in New Zealand from 1990–91 to 2020–21 (Moot and Davison 2021). Figures for 2020–21 are provisional. (Note: This figure was produced from data supplied by the Beef + Lamb New Zealand Economic Service and includes Stats NZ's data which are licensed by Stats NZ for reuse under the Creative Commons Attribution 4.0 International licence).

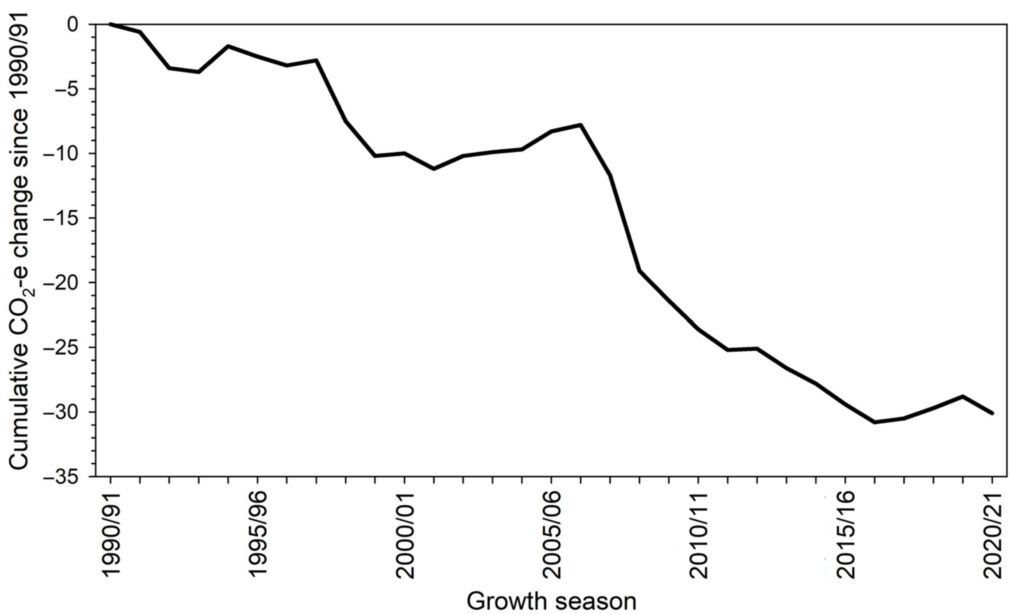

Fig. 7. Cumulative decrease (%) in warming from CH_4 and N_2O, expressed as CO_2-e, from sheep and beef cattle in New Zealand over 30 years from 1990/91 to 2020/21. Figures for 2020/21 are provisional. (Note: This figure was produced from data supplied by the Beef + Lamb New Zealand Economic Service and includes Stats NZ's data, which are licensed by Stats NZ for reuse under the Creative Commons Attribution 4.0 International licence).

total emissions (Ministry for the Environment 2021). Dealing with this fact has become a political issue. The government has set goals for further reductions of emissions from the agriculture sector. In the absence of practical CH_4 inhibitors (Leahy *et al.* 2019) or other technologies, it is likely that in the medium term these can only be achieved by further reducing the mean time from birth to slaughter for sheep and cattle (Moot and Davison 2021), which results in lower emissions and reduced maintenance respiration (de Klein *et al.* 2008). In short, productivity gains based around the increased use of high quality forages, predominantly legumes, has transformed the sheep and beef sector and is a viable option to further reduce their emissions in the foreseeable future. On average, 14% of hill and high country farms are covered by a combination of exotic forestry (2%), native bush, woody scrub vegetation and wetlands (12%) (Moot and Davison 2021), which means these farms are close to or already carbon neutral (Case and Ryan 2020).

For dairy, emissions have increased because cattle numbers have increased from 3.4 M in 1990 to 6.1 M in 2021 (Moot and Davison 2021). This has been the main contributor to the 17% rise in total emissions from agriculture over the same period (Ministry for the Environment 2022). However, the emissions intensity from New Zealand dairy cows is the lowest in the world at 0.77 kg CO_2-e per unit of fat corrected protein compared with a global average of 1.47 (Mazetto *et al.* 2021). If there is an increase in pasture legume content as a result of the new rules on N fertiliser (Myint *et al.* 2021) then further reductions in emission intensity may be possible. To date, other investigations into reducing greenhouse gas emissions from pasture-fed dairy cows have failed to produce practical on-farm solutions. Thus, the restriction to 190 kg N/ha will most likely result in reduced stocking rates and total stock numbers, plus lower N_2O emissions from less inorganic fertiliser use. Indeed the independent, but government appointed, Climate Change Commission has recently advocated for a direct tax on N fertiliser, which may encourage even greater use of legumes on-farm in the next 30 years.

Conclusions

The New Zealand pastoral sector will remain the most important contributor to the wealth of the country for the foreseeable future. The use of legumes to provide the N required to optimise plant and animal production has been, and will continue to be, a key component of that success. The interaction of species (G), environment (E) and management (M) has meant different issues have needed to be addressed across the diverse New Zealand landscape to support the pastoral-based livestock industries. For summer dry regions, the research has focused on increased lucerne management flexibility, dealing with associated animal health concerns and the extension of exemplars of transformational change on-farm. Greater adoption of appropriate subterranean clover grazing management on hill country has been promoted to complement lucerne growing on cultivatable ground. In ‘summer safe’, higher-rainfall hill country environments, a satellite farming approach of legume (red clover) monocultures or legume and herb mixes has the potential to ensure the productivity gains made over the last 30 years can be continued into the future. The key to success has been to ensure the right legume is put in the right environment and, importantly, that there is an appropriate management package developed to support on-farm adoption. This requires ongoing high quality research through on-station experiments, coupled with model development to answer questions around impacts on land use and climate change. At the same time there is a need to maintain on-farm demonstrations and case studies that are most relevant to the farming communities that ultimately have the task of producing food under increasing legislative and consumer requirements. For future success, the New Zealand Government and levy-based industries must continue to invest in the primary sector to ensure the tools are available to deliver at all levels of the value chain, across the mosaic of landscapes within geographically distinct regions of New Zealand.

References

Addiscott TM (2005) ‘Nitrate, agriculture and the environment.’ p. 279. (CABI International: Wallingford, UK)

Anderson D, Anderson L, Moot DJ, Ogle GI (2014) Integrating lucerne (*Medicago sativa* L.) into a high country merino system. *Proceedings of the New Zealand Grassland Association* **76**, 29–34. doi:10.33584/jnzg.2014.76.2951

Avery D, Avery F, Ogle GI, Wills BJ, Moot DJ (2008) Adapting farm systems to a drier future. *Proceedings of the New Zealand Grassland Association* **70**, 13–18. doi:10.33584/jnzg.2008.70.2710

Barry TN, McNabb WC, Kemp PD, Waghorn GC, Min BR, Luque A (1999) The effect of condensed tannins in *Lotus corniculatus* upon reproductive efficiency and wool production in sheep during late summer and autumn. *Proceedings of the New Zealand Grassland Association* **61**, 51–55. doi:10.33584/jnzg.1999.61.2354

Barry TN, Kemp PD, Ramirez-Restrepo CA, Lopez-Villalobos N (2003) Sheep production and agronomic performance of *Lotus corniculatus* under dryland farming. *Legumes for Dryland Pastures - Grassland Research and Practice Series* **11**, 109–115. doi:10.33584/rps.11.2003.3003

Beef + Lamb New Zealand Economic Service, Statistics New Zealand (2022) Canterbury farm number and dairy area (Dataset). (Beef + Lamb New Zealand Economic Service and Statistics New Zealand)

Berenji S, Moot DJ, Moir JL, Ridgway HJ (2015) Lucerne dry matter and N-fixation, when sown with or without lime and inoculant. *Journal of New Zealand Grasslands* **77**, 109–116. doi:10.33584/jnzg.2015.77.497

Berenji S, Moot DJ, Moir JL, Ridgway H, Rafat A (2017) Dry matter yield, root traits, and nodule occupancy of lucerne and Caucasian clover when grown in acidic soil with high aluminium concentrations. *Plant and Soil* **416**(1/2), 227–241. doi:10.1007/s11104-017-3203-3

Berenji S, Mills A, Moir JL, Pollock KM, Murray W, Murray E, Moot DJ (2018) Dry matter yield of six perennial legume species in response to lime over 3 years at Glenmore Station, Mackenzie Basin. *Journal of New Zealand Grasslands* **80**, 81–90. doi:10.33584/jnzg.2018.80.338

Berone GD, Sardina MC, Moot DJ (2020) Animal and forage responses on lucerne (*Medicago sativa* L.) pastures under contrasting grazing managements in a temperate climate. *Grass and Forage Science* **75**, 192–205. doi:10.1111/gfs.12479

Black AD, Ryan-Salter TP (2016) Evaluation of perennial lupin/cocksfoot pasture relative to lucerne pasture under summer dry conditions. *Journal of New Zealand Grasslands* **78**, 123–132. doi:10.33584/jnzg.2016.78.530

Black AD, Moot DJ, Lucas RJ (2006*a*) Spring and autumn establishment of Caucasian and white clovers with different sowing rates of perennial ryegrass. *Grass and Forage Science* **61**(4), 430–441. doi:10.1111/j.1365-2494.2006.00552.x

Black AD, Moot DJ, Lucas RJ (2006*b*) Development and growth characteristics of Caucasian and white clover seedlings, compared with perennial ryegrass. *Grass and Forage Science* **61**(4), 442–453. doi:10.1111/j.1365-2494.2006.00553.x

Black AD, Harvey AJ, Moir JL, Moot DJ (2014*a*) Caucasian clover responses to fertiliser, lime and rhizobia inoculation at Lake Heron Station, Canterbury. *Proceedings of the New Zealand Grassland Association* **76**, 105–109. doi:10.33584/jnzg.2014.76.2967

Black AD, Loxton G, Ryan-Salter TP, Moot DJ (2014*b*) Sheep performance on perennial lupins over three years at Sawdon Station, Lake Tekapo. *Proceedings of the New Zealand Grassland Association* **76**, 35–39. doi:10.33584/jnzg.2014.76.2958

Black AD, Loxton G, Ryan-Salter TP, Moot DJ (2015) Merino lamb and wool production from a commercial stand of perennial lupin (*Lupinus polyphyllus*) on a high country farm in New Zealand. In 'Proceedings of the XIV international lupin conference'. Milan, Italy p. 36.

Black AD, Myint TS, Shampasivam A, Yang S (2021) Plant diversity with species drilled in the same or alternate rows enhanced pasture yield and quality over 4 years. *Resilient Pastures – Grassland Research and Practice Series* **17**, 263–274. doi:10.33584/rps.17.2021.3470

Brock JL, Caradus JR, Hay MJM (1989) Fifty years of white clover research in New Zealand. *Proceedings of the New Zealand Grassland Association* **50**, 25–39. doi:10.33584/jnzg.1989.50.1868

Brown HE, Moot DJ, Pollock KM (2005) Herbage production, persistence, nutritive characteristics and water use of perennial forages grown over 6 years on a Wakanui silt loam. *New Zealand Journal of Agricultural Research* **48**, 423–439. doi:10.1080/00288233.2005.9513677

Caradus JR, Woodfield DR, Stewart AV (1995) Overview and vision for white clover. *White Clover: New Zealand's Competitive Edge - Grassland Research and Practice Series* **6**, 1–6. doi:10.33584/rps.6.1995.3368

Caradus JR, Goldson SL, Moot DJ, Rowarth JS, Stewart AV (2021) Pastoral agriculture, a significant driver of New Zealand's economy, based on an introduced grassland ecology and technological advances. *Journal of the Royal Society of New Zealand*. doi:10.1080/03036758.2021.2008985

Carberry PS (2001) Are science rigour and industry relevance both achievable in participatory action research? In 'Science and technology: delivering results for agriculture?. Proceedings of the 10th Australian agronomy conference'. January 2001. (Eds B Rowe, D Donaghy, N Mendham) (Australian Agronomy Society: Hobart, Tasmania) Available at http://www.regional.org.au/au/asa/2001/plenary/5/carberry.htm#TopOfPage

Carrick S, Palmer D, Webb T, Scott J, Lilburne L (2013) Stony soils are a major challenge for nutrient management under irrigation development. In 'Accurate and efficient use of nutrients on farms'. Occasional Report No. 26. (Eds LD Currie, CL Christensen) pp. 8. (Fertilizer and Lime Research Centre, Massey University: Palmerston North, New Zealand)

Case B, Ryan C (2020) An analysis of carbon stocks and net carbon position for New Zealand sheep and beef farmland. Department of Applied Ecology, School of Science, Auckland University of Technology, New Zealand.

Chapman J, Smith M, Lucas R, Moot D (2021) Legumes are the key to increasing productivity at 'Inverary', a summer moist hill/high country farm in mid-Canterbury. *Journal of New Zealand Grasslands* **83**, 51–58. doi:10.33584/jnzg.2021.83.3516

Cosgrove GP (2005) Novel grazing management: making better use of white clover. In ''SIDE by SIDE'. Proceedings of the 2005 South Island Dairy Event (SIDE) conference'. 20–22 June 2005. (Lincoln University: Canterbury, New Zealand). (ISBN 0864761643). Available at https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.564.7992&rep=rep1&type=pdf

Costello T, Costello A (2003) Subterranean clover in North Canterbury sheep pastures. *Legumes for Dryland Pastures - Grassland Research and Practice Series* **11**, 189–192. doi:10.33584/rps.11.2003.3011

de Klein CAM, Pinares-Patino C, Waghorn GC (2008) Greenhouse gas emissions. In 'Environmental impacts of pasture-based farming'. (Ed. RW McDowell) pp. 1–33. (CAB International: Wallingford, UK)

Di HJ, Cameron KC (2002) Nitrate leaching and pasture production from different nitrogen sources on a shallow stoney soil under flood-irrigated dairy pasture. *Soil Research* **40**(2), 317–334. doi:10.1071/SR01015

Dymond JR, Ausseil A-GE, Parfitt RL, Herzig A, McDowell RW (2013) Nitrate and phosphorus leaching in New Zealand: a national perspective. *New Zealand Journal of Agricultural Research* **56**(1), 49–59. doi:10.1080/00288233.2012.747185

Eerens JPJ, Hardwick S, Gerard PJ, Willoughby BE (2005) Clover root weevil (*Sitona lepidus*) in New Zealand: the story so far. *Proceedings of the New Zealand Grassland Association* **67**, 19–22. doi:10.33584/jnzg.2005.67.2588

Evans LT (1998) 'Feeding the ten billion: plants and population growth.' p. 264. (Cambridge University Press: Cambridge, UK)

Fields RL, Barrell GK, Moot DJ (2016) Premature mammary development in ewe lambs exposed to an oestrogenic lucerne pasture. *Journal of New Zealand Grasslands* **78**, 41–44. doi:10.33584/jnzg.2016.78.518

Fields RL, Barrell GK, Gash A, Zhao J, Moot DJ (2018) Alfalfa coumestrol content in response to development stage, fungi, aphids, and cultivar. *Agronomy Journal* **110**(3), 910–921. doi:10.2134/agronj2017.09.0535

Fields RL, Moot DJ, Sedcole JR, Barrell GK (2019) Recovery of ovulation rate in ewes following their removal from an oestrogenic lucerne forage. *Animal Production Science* **59**(3), 493–498. doi:10.1071/AN17586

Ford JL, Barrett BA (2011) Improving red clover persistence under grazing. *Proceedings of the New Zealand Grassland Association* **73**, 119–124. doi:10.33584/jnzg.2011.73.2838

Grigg DW, Grigg JM, Lucas RJ (2008) Maximising subterranean clover in Marlborough's hill country is key to weaning 80% of sale lambs prime. *Proceedings of the New Zealand Grassland Association* **70**, 25–29. doi:10.33584/jnzg.2008.70.2727

Guo J, Teixeira CSP, Barringer J, Hampton JG, Moot DJ (2022) Estimation of time to key phenological stages to guide management of subterranean clover (*Trifolium subterraneum* L.) in New Zealand. *European Journal of Agronomy* **134**, 126451. doi:10.1016/j.eja.2021.126451

Harris SL, Clark DA, Laboyrie PJ (1998) Birdsfoot trefoil – an alternative legume for New Zealand dairy pastures. *Proceedings of the New Zealand Grassland Association* **60**, 99–103. doi:10.33584/jnzg.1998.60.2314

Haslin E, Corner-Thomas RA, Kenyon PR, Pettigrew EJ, Hickson RE, Morris ST, Blair HT (2022) Effects of heavier live weight of ewe lambs at mating on fertility, lambing percentage, subsequent live weight and the performance of their progeny. *New Zealand Journal of Agricultural Research* **65**(2-3), 114–128. doi:10.1080/00288233.2020.1840399

Hurst RGM, Black AD, Lucas RJ, Moot DJ (2000) Sowing strategies for slow-establishing pasture species on a North Otago dairy farm. *Proceedings of the New Zealand Grassland Association* **62**, 129–135. doi:10.33584/jnzg.2000.62.2381

Jáuregui JM, Mills A, Black DBS, Wigley K, Ridgway HJ, Moot DJ (2019) Yield components of lucerne were affected by sowing dates and inoculation treatments. *European Journal of Agronomy* **103**, 1–12. doi:10.1016/j.eja.2018.10.005

Jones CA, Williams WA, Hancock K, Ellison N, Scott A, Collette V, Jahufer Z, Richardson K, Hay MJM, Rasmussen S, Jones CA, Griffiths A (2006) Pastoral Genomics – a foray into the clover genome. *Advances in Plant Breeding - Research & Practice Series* **12**, 21–23. doi:10.33584/rps.12.2006.3035

Knowles IM, Fraser TJ, Daly MJ (2003) White clover: loss in drought and subsequent recovery. *Legumes for Dryland Pastures - Grassland Research and Practice Series* **11**, 37–41. doi:10.33584/rps.11.2003.2997

Lane PMS, Lee SA, Willoughby BE (2016) Hill country cropping with no land-based equipment. *Hill Country Symposium - Journal of New Zealand Grasslands* **16**, 251–256. doi:10.33584/rps.16.2016.3246

Leahy SC, Kearney L, Reisinger A, Clark H (2019) Mitigating greenhouse gas emissions from New Zealand pasture-based livestock farm systems. *Journal of New Zealand Grasslands* **81**, 101–110. doi:10.33584/jnzg.2019.81.417

Ledgard SF (2017) Assessing the environmental impact of sheep production. In 'Achieving sustainable production of sheep'. (Ed. J Greyling) pp. 407–430. (Burleigh Dodds Science Publishing Limited: Cambridge, UK)

Lewis TR, Lucas RJ, Hofmann RW, Moot DJ (2017) Tolerance of newly sown cocksfoot-clover pastures to the herbicide imazethapyr. *Journal of New Zealand Grasslands* **79**, 173–180. doi:10.33584/jnzg.2017.79.552

LIC and DairyNZ (2021) New Zealand dairy statistics 2020–21. Available at https://www.dairynz.co.nz/publications/dairy-industry/new-zealand-dairy-statistics-2020-21/ [Accessed 22 June 2022]

Lowther WL, Kerr GA (2011) White clover seed inoculation and coating in New Zealand. *Proceedings of the New Zealand Grassland Association* **73**, 93–102. doi:10.33584/jnzg.2011.73.2841

Lucas RJ, Smith MC, Jarvis P, Mills A, Moot DJ (2010) Nitrogen fixation by subterranean and white clovers in dryland cocksfoot pastures. *Proceedings of the New Zealand Grassland Association* **72**, 141–146. doi:10.33584/jnzg.2010.72.2825

Lucas RJ, Mills A, Wright S, Black AD, Moot DJ (2015) Selection of sub clover cultivars for New Zealand dryland pastures. *Journal of New Zealand Grasslands* **77**, 203–210. doi:10.33584/jnzg.2015.77.459

Macfarlane MJ, Crofoot EW, Muir PD (2015) Effects of closing date on seeding and hardseededness of balansa, gland, Persian and arrowleaf clovers on East Coast dryland. *Journal of New Zealand Grasslands* **77**, 219–226. doi:10.33584/jnzg.2015.77.461

Mangwe MC, Bryant RH (2021) Partial replacement of ryegrass and clover herbage with chicory to alter urination behaviour and soil nitrogen loading of grazing dairy cows. *Journal of New Zealand Grasslands* **83**, 179–188. doi:10.33584/jnzg.2021.83.3507

Mazetto A, Falconer S, Ledgard S (2021) Mapping the carbon footprint of milk for dairy cows. Report for DairyNZ (No. RE450/2020/081). AgResearch, Hamilton. p. 22. Available at https://www.dairynz.co.nz/media/5794083/mapping-the-carbon-footprint-of-milk-for-dairy-cows-report-updated.pdf

Mills A, Moot DJ, McKenzie BA (2006) Cocksfoot pasture production in relation to environmental variables. *Proceedings of the New Zealand Grassland Association* **68**, 89–94. doi:10.33584/jnzg.2006.68.2636

Mills A, Moot DJ, Jamieson PD (2009) Quantifying the effect of nitrogen on productivity of cocksfoot (*Dactylis glomerata* L.) pastures. *European Journal of Agronomy* **30**, 63–69. doi:10.1016/j.eja.2008.07.008

Mills A, Lucas RJ, Moot DJ (2015) 'MaxClover' grazing experiment: I. Annual yields, botanical composition and growth rates of six dryland pastures over nine years. *Grass and Forage Science* **70**, 557–570. doi:10.1111/gfs.12132

Ministry for the Environment (2021) 'New Zealand's Greenhouse Gas Inventory 1990–2019.' p. 507. (Ministry for the Environment: Wellington, New Zealand) Available at https://environment.govt.nz/assets/Publications/New-Zealands-Greenhouse-Gas-Inventory-1990-2019-Volume-1-Chapters-1-15.pdf

Ministry for the Environment (2022) New Zealand's greenhouse gas inventory 1990–2020. Te Rārangi Haurehu Kati Mahana a Aotearoa 1990-2020. (Emissions by Sector). Available at https://environment.govt.nz/assets/publications/Greenhouse-Gas-Inventory-Snapshot-English-final.pdf [Accessed 8 September 2022]

Minnée EMK, Leach CMT, Dalley DE (2020) Substituting a pasture-based diet with plantain (*Plantago lanceolata*) reduces nitrogen excreted in urine from dairy cows in late lactation. *Livestock Science* **239**, 104093. doi:10.1016/j.livsci.2020.104093

Molan AL, Waghorn GC, McNabb WC (1999) Condensed tannins and gastro-intestinal parasites in sheep. *Proceedings of the New Zealand Grassland Association* **61**, 57–61. doi:10.33584/jnzg.1999.61.2363

Monk S, Moot DJ, Belgrave BR, Rolston MP, Caradus JR (2016) Availability of seed for hill country adapted forage legumes. *Hill Country Symposium - Journal of New Zealand Grasslands* **16**, 257–267. doi:10.33584/rps.16.2016.3237

Monks DP, Moot DJ, Smith MC, Lucas RJ (2008) Grazing management for regeneration of balansa clover in a cocksfoot pasture. *Proceedings of the New Zealand Grassland Association* **70**, 233–238. doi:10.33584/jnzg.2008.70.2701

Moot DJ, Davison R (2021) Changes in New Zealand red meat production over the past 30 yr. *Animal Frontiers* **11**(4), 26–31. doi:10.1093/af/vfab027

Moot DJ, Brown HE, Teixeira EI, Pollock KM (2003) Crop growth and development affect seasonal priorities for lucerne management. *Legumes for Dryland Pastures - Journal of New Zealand Grasslands* **11**(No. 11), 201–208. doi:10.33584/rps.11.2003.3007

Moot DJ, Bennett SM, Mills AM, Smith MC (2016) Optimal grazing management to achieve high yields and utilisation of dryland lucerne. *Journal of New Zealand Grasslands* **78**, 27–34. doi:10.33584/jnzg.2016.78.516

Moot DJ, Anderson PVA, Anderson LJ, Anderson DK (2019) Animal performance changes over 11 years after implementing a lucerne grazing system on Bog Roy Station. *Journal of New Zealand Grasslands* **81**, 75–80. doi:10.33584/jnzg.2019.81.390

Moot DJ, Black AD, Mills A (2020*a*) New Zealand drivers of pasture production and options available to improve composition and management. In 'Growing with grasslands. Proceedings of the 61st Annual Grassland Society of Southern Australia (GSSA) virtual conference'. pp. 50–54. (Grassland Society of Southern Australia (GSSA))

Moot DJ, Smith MC, Mills A (2020*b*) Liveweight production, dry matter yield and seasonal composition from dryland lucerne and lucerne/grass mixes over five years. *New Zealand Journal of Agricultural Research* **63**, 272–300. doi:10.1080/00288233.2019.1645703

Moot DJ, Yang X, Ta HT, Brown HE, Teixeira EI, Sim RE, Mills A (2022) Simplified methods for on-farm prediction of yield potential of grazed lucerne crops in New Zealand. *New Zealand Journal of Agricultural Research* **65**(4-5), 252–270. doi:10.1080/00288233.2021.1909078

Myint TS, Black AD, Moot DJ (2021) Nitrogen effects on species' contributions to grazed pasture mixtures under nitrogen loss and application restrictions. *Journal of New Zealand Grasslands* **83**, 25–34. doi:10.33584/jnzg.2021.83.3513

Navarrete S, Rodriguez M, Horne D, Hanly J, Hedley M, Kemp P (2022) Nitrogen excretion by dairy cows grazing plantain (*Plantago lanceolata*) based pastures during the lactating season. *Animals* **12**(4), 469. doi:10.3390/ani12040469

Nori H, Moot DJ, Black AD (2015*a*) Dry matter yield and radiation use efficiency of four autumn sown top flowering annual clovers. *Journal of New Zealand Grasslands* **77**, 185–194. doi:10.33584/jnzg.2015.77.470

Nori H, Monks DP, Moot DJ (2015*b*) Seed development of arrowleaf, balansa, gland and Persian clovers. *Journal of New Zealand Grasslands* **77**, 195–202. doi:10.33584/jnzg.2015.77.457

Nori H, Moot DJ, Mills A (2019) Seed production, seedling regeneration and hardseeds breakdown of annual clovers. *New Zealand Journal of Agricultural Research* **62**, 316–331. doi:10.1080/00288233.2018.1488747

Olykan ST, Lucas RJ, Nicholson DJ, Doscher C, Moot DJ (2019) Maximising the subterranean clover content on a summer-dry Wairarapa hill-country farm through grazing management. *Journal of New Zealand Grasslands* **81**, 91–100. doi:10.33584/jnzg.2019.81.391

Olykan ST, Lucas RJ, Hunter SR, Moot DJ (2021) Growth rates and persistence of annual and perennial clovers. *Journal of New Zealand Grasslands* **83**, 69–78. doi:10.33584/jnzg.2021.83.3494

Olykan ST, Doscher C, Lucas RJ, Nicholson DJ, Moot DJ (2022) Mapping groundcover of clover species in hill pastures in Wairarapa. *Journal of New Zealand Grasslands* **84**.

Peoples MB, Brockwell J, Hunt JR, Swan AD, Watson L, Hayes RC, Li GD, Hackney B, Nuttall JG, Davies SL, Fillery IRP (2012) Factors affecting the potential contributions of N_2 fixation by legumes in Australian pasture systems. *Crop & Pasture Science* **63**(9), 759–786. doi:10.1071/CP12123

Peri PL, Moot DJ, McNeil DL, Lucas RJ (2003) Modelling net photosynthetic rate of field-grown cocksfoot leaves to account for regrowth duration. *New Zealand Journal of Agricultural Research* **46**, 105–115. doi:10.1080/00288233.2003.9513536

Pryor HN, Lowther WL, McIntyre HJ, Ronson CW (1998) An inoculant *Rhizobium* strain for improved establishment and growth of hexaploid Caucasian clover (*Trifolium ambiguum*). *New Zealand Journal of Agricultural Research* **41**(2), 179–189. doi:10.1080/00288233.1998.9513301

Ryan-Salter TP, Black AD, Andrews M, Moot DJ (2014) Identification and effectiveness of rhizobial strains that nodulate *Lupinus polyphyllus*. *Proceedings of the New Zealand Grassland Association* **76**, 61–65. doi:10.33584/jnzg.2014.76.2961

Scott D (1989) Perennial or Russell lupin: a potential high country pasture legume. *Proceedings of the New Zealand Grassland Association* **50**, 203–206. doi:10.33584/jnzg.1989.50.1886

Scott D (2001) Sustainability of New Zealand high-country pastures under contrasting development inputs. 7. Environmental gradients, plant species selection, and diversity. *New Zealand Journal of Agricultural Research* **44**(1), 59–90. doi:10.1080/00288233.2001.9513463

Scott D (2014) The rise to dominance over two decades of *Lupinus polyphyllus* among pasture mixtures in tussock grassland trials. *Proceedings of the New Zealand Grassland Association* **76**, 47–52. doi:10.33584/jnzg.2014.76.2959

Seth K (2017) Functional and community investigation of nodule endophytes for the selection of phosphate solubilizing rhizobial inoculants for clover. PhD Thesis, Lincoln University, Lincoln, New Zealand. Available at https://hdl.handle.net/10182/10107

Shah AS (2019) An investigation of the ecology of rhizobia that nodulate white and subterranean clovers in response to soil pH. PhD Thesis, Lincoln University, Lincoln, New Zealand. Available at https://hdl.handle.net/10182/11845

Shah AS, Wakelin SA, Moot DJ, Blond C, Laugraud A, Ridgway HJ (2021) *Trifolium repens* and *T. subterraneum* modify their nodule microbiome in response to soil pH. *Journal of Applied Microbiology* **131**, 1858–1869. doi:10.1111/jam.15050

Shah AS, Wakelin SA, Moot DJ, Blond C, Noble A, Ridgway HJ (2022) High throughput pH bioassay demonstrates pH adaptation of *Rhizobium* strains isolated from the nodules of *Trifolium subterraneum* and *T. repens*. *Journal of Microbiological Methods* **195**, 106455. doi:10.1016/j.mimet.2022.106455

Sheaffer CC, Lacefield GD, Marble VL (1988) Cuting schedules and stands. In 'Alfalfa and alfalfa improvement'. (Eds AA Hanson, DK Barnes, RR Hll Jr.) pp. 411–437. (American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.: Madison, WI, USA)

Sim RE, Moot DJ (2019) The influence of spring grazing management on yield and water use of rainfed lucerne. *Journal of New Zealand Grasslands* **81**, 187–194. doi:10.33584/jnzg.2019.81.403

Smith MC, Mills A, Moot DJ (2022) Total annual and seasonal DM production of improved and unimproved resident pastures at three farms in Canterbury. *Journal of New Zealand Grasslands* **84**.

Snowball R (1993) Preliminary agronomic evaluation and characterisation of Persian clover (*Trifolium resupinatum* L.). *Australian Plant Introduction Review* **24**, 10–41. Available at https://discovery.csiro.au/view/delivery/61CSIRO_INST/12120360410001981

Statistics New Zealand (2022) National stock numbers – Variable by Total New Zealand (Annual-Jun). Available at https://infoshare.stats.govt.nz/SelectVariables.aspx?pxID=aef4d837-f270-41ab-a300-5bafd4a4085d [Accessed 1 July 2022]

Stevens DR, Garden JP, Garden N, Casey MJ (2020) Can *Lotus pedunculatus* over-sowing in low-fertility tussock country increase farm resilience? *Journal of New Zealand Grasslands* **82**, 171–181. doi:10.33584/jnzg.2020.82.3429

Ta HT, Teixeira EI, Brown HE, Moot DJ (2020) Yield and quality changes in lucerne of different fall dormancy ratings under three defoliation regimes. *European Journal of Agronomy* **115**, 126012. doi:10.1016/j.eja.2020.126012

Tayler M, Donnelly L, Frater P, Stocker N (2016) Lorne Peak Station – achieving sustainable profitability in challenging Southland hill country. *Hill Country Symposium - Journal of New Zealand Grasslands* **16**, 101–108. doi:10.33584/rps.16.2016.3264

Taylor BJO (2019) Yield and botanical composition of subterranean clover in response to ALS inhibiting herbicides and waterlogging. M.Ag.Sci. Thesis, Lincoln University, Lincoln, New Zealand. Available at https://hdl.handle.net/10182/11438

Taylor BJO, Mills A, Smith M, Lucas RJ, Moot DJ (2021) Yield and botanical composition of four dryland pastures at Ashley Dene Research Farm over 8 years. *Resilient Pastures – Journal of New Zealand Grasslands* **17**, 275–284. doi:10.33584/rps.17.2021.3445

Teixeira CSP, Hampton JG, Moot DJ (2020*a*) Reproductive development in subterranean clover (*Trifolium subterraneum* L.): a reanalysis of Oceania datasets. *European Journal of Agronomy* **119**, 126123. doi:10.1016/j.eja.2020.126123

Teixeira CSP, Lucas RJ, Olykan ST, Moot DJ (2020*b*) Causes of leaf reddening in subterranean clover cultivars. *New Zealand Journal of Agricultural Research* **63**(3), 315–331. doi:10.1080/00288233.2020.1754244

Tozer KN, Douglas GB (2016) Pasture establishment on non-cultivable hill country: a review of the New Zealand literature. *Hill Country Symposium – Journal of New Zealand Grasslands* **16**, 213–224. doi:10.33584/rps.16.2016.3233

van der Weerden TJ, Luo J, Di HJ, Podolyan A, Phillips RL, Saggar S, de Klein CAM, Cox N, Ettema P, Rys G (2016) Nitrous oxide emissions from urea fertiliser and effluent with and without inhibitors applied to pasture. *Agriculture, Ecosystems & Environment* **219**, 58–70. doi:10.1016/j.agee.2015.12.006

van Ittersum MK (2011) Future Harvest: the fine line between myopia and utopia. Inaugural lecture upon taking up the post of Personal Professor of Plant Production Systems at Wageningen University on 12 May 2011. p. 34. (Wageningen University: Netherlands) Available at https://edepot.wur.nl/169680

Waghorn GC, Tavendale MH, Woodfield DR (2002) Methanogenesis from forages fed to sheep. *Proceedings of the New Zealand Grassland Association* **64**, 167–171. doi:10.33584/jnzg.2002.64.2462

Widdup KH, Hussain SW, Williams WM, Lowther WL, Pryor HN, Sutherland BL (2003) The development and plant characteristics of interspecific hybrids between white and caucasian clover. *Legumes for Dryland Pastures - Journal of New Zealand Grasslands* **11**, 143–148. doi:10.33584/rps.11.20c03.3004

Wigley K, Liu WYY, Khumalo Q, Moot DJ, Brown DS, Ridgway HJ (2015) Effectiveness of three inoculation methods for lucerne (*Medicago sativa* L.) in two Canterbury soils. *New Zealand Journal of Agricultural Research* **58**(3), 292–301. doi:10.1080/00288233.2015.1028652

Wigley K, Ridgway H, Moot DJ (2016*a*) The survival of the commercial inoculant in white clover and lucerne. In 'Growing landscapes – Cultivating innovative agricultural systems. Proceedings of the 14th annual conference of the European Agronomy Society'. 5-9 September 2016. pp. 21–22. (European Agronomy Society: Edinburgh, Scotland)

Wigley K, Wakelin SA, Moot DJ, Hammond S, Ridgway HJ (2016*b*) Measurements of carbon utilization by single bacterial species in sterile soil: insights into *Rhizobium* spp. *Journal of Applied Microbiology* **121**(2), 495–505. doi:10.1111/jam.13170

Wigley K, Moot D, Wakelin SA, Laugraud A, Blond C, Seth K, Ridgway H (2017) Diverse bacterial taxa inhabit root nodules of lucerne (*Medicago sativa* L.) in New Zealand pastoral soils. *Plant and Soil Science* **420**(1-2), 253–262. doi:10.1007/s11104-017-3395-6

Woodfield DR (Ed.) (1995) 'White clover: New Zealand's competitive edge.' Grassland Research and Practice Series No. 6/Agronomy New Zealand Special Publication No. 11. p.178. (New Zealand Grassland Association/Agronomy Society of New Zealand: Palmerston North, NZ)

Woodward SL, Chaves AV, Waghorn GC, Laboyrie PG (2002) Supplementing pasture-fed dairy cows with pasture silage, maize silage, Lotus silage or sulla silage in summer - does it increase production? *Proceedings of the New Zealand Grassland Association* **64**, 85–89. doi:10.33584/jnzg.2002.64.2479

Yang X, Brown HE, Teixeira EI, Moot DJ (2021) Development of a lucerne model in APSIM next generation: 1 phenology and morphology of genotypes with different fall dormancies. *European Journal of Agronomy* **130**, 126372. doi:10.1016/j.eja.2021.126372

Yang X, Brown HE, Teixeira EI, Moot DJ (2022) Development of a lucerne model in APSIM next generation: 2 canopy expansion and light interception of genotypes with different fall dormancy ratings. *European Journal of Agronomy* **139**, 126570. doi:10.1016/j.eja.2022.126570

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