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REVIEW ARTICLE

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# Pastoral agriculture, a significant driver of New Zealand's economy, based on an introduced grassland ecology and technological advances*

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**ABSTRACT**
The New Zealand economy is export-driven and heavily reliant on the productivity of the pastoral sector. The transformation of native forest and tussock grassland ecologies to temperate grasslands occurred rapidly with the arrival of Europeans. However, this transplanted ecology required the development and use of plant, microbial, animal and management technologies for successful grassland farming. These have enabled New Zealand pastoral agriculture to compete effectively in international markets, without subsidies. The extensive list of plant-based and associated microbial-based adaptations, and the management strategies that have enabled the development of highly productive grasslands are described and reviewed. Credible science is required to inform the debate on the environmental impacts of pasture production to avoid misinformation proliferating. This needs transparent and objective integrity from the science community using funding that seeks no defined or preconceived outcomes. Critically, much of the success of New Zealand pastoral farming has been due to the willingness and ability of farmers to use, adapt, adopt and integrate new ideas and technologies into their farming systems. Historic, current and future challenges, and threats that impact on the productivity and sustainability of pastoral agriculture are described and the means to achieve further technology development to manage these is discussed.

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## Introduction

Prior to human arrival 800 years ago (Wilmshurst et al. 2008, 2011), about 85% of New Zealand was covered in rainforest (King 1984; Haggerty and Campbell 2008). Natural tussock grasslands occurred only in subalpine regions or those with less than 600–

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700 mm of annual precipitation (McGlone 1989). These are largely on the east coast and central areas of both islands. Both Māori and European settlers, to varying degrees, changed this landscape by clearing forest and tussock, and draining swamps to create farmland. The plant and animal species required for this transformation were introduced largely from Western Europe, and particularly the United Kingdom (Clark 1949). This followed the international process of deforestation and agricultural development to feed an increasing global population. In New Zealand, 29% of the land area remains in indigenous forest (Ministry for Primary Industries), and the rural landscape is dominated by grassland that supports dairy, beef, sheep and deer farming operations (McGlone 1989), but with significant areas used for forestry, horticulture and cropping. Indeed, it was pastoral farming that ensured New Zealand achieved one of the highest standards of living in the world (Singleton 2008) and it remains the only OECD country that owes its economic position to a bioeconomy based on pastoral farming, which provides nearly 50% of export value (OECD 2019; Ministry of Primary Industries 2021).

The introduced grasslands of New Zealand are predominantly temperate in composition, based on perennial grasses, legumes, herbs and annual forage crops such as maize (*Zea mays*) and brassicas (*Brassica* species). Most species were first introduced in the mid-1800s and expansion of areas into grasslands continued for over 100 years. The following quote used by G. H. Holford highlights the perceived (and real) importance of grassland farming to the New Zealand economy – 'After air, light and water, the next most important thing is grass. We all know it exists in all lands to some extent, but there is no country in the world so dependent on grass as New Zealand' (Holford 1933). This statement has remained true throughout a century of intensification that has increased productivity underpinned by agricultural science that has informed farm management and developed new technologies (Caradus and Clark 2001; McIvor and Aspin 2001; Woodfield 2002; Lissaman et al. 2013). The questions to be examined in this contribution are:

(a) What plant and associated microbial adaptations and management strategies have enabled the achievement of highly productive grassland from forest?
(b) What future plant and microbial adaptations and management strategies are required to ensure pastoral agriculture remains sustainable as the major contributor to the New Zealand economy?
(c) What disruptions to the environment and the economy have there been from the introduction of grassland and subsequent intensification?
(d) How have previous biosecurity breaches affected grassland production and what are the potential impacts and required management strategies for the future?
(e) What current and future threats will impact on the productivity and sustainability of pastoral agriculture?
(f) Can managed grassland be both productive and sustainable?

The motivation here is to record in a reputable scientific journal the excellent research, development, and innovative farmer practice that has established and continues to support New Zealand's grazed pastoral systems which form the economic base ensuring the country's prosperity.

## Pre-European climax vegetation and landscapes

Māori brought plants from Polynesia which included kūmara (sweet potato, *Ipomoea batatas*), hue (bottle gourd, *Lagenaria siceraria*), aute (paper mulberry, *Broussonetia papyrifera*), taro (*Colocasia esulenta*), uwhi (yam, *Dioscorea* species), and tī pore (Pacific cabbage tree, *Cordyline fruticosa*) (Te Ara 2008a). Initially the small Polynesian population had limited impact, but increasing numbers, combined with a climate slowly warming, led to a peak destruction of forests between ∼750 and 500 years ago (Argiriadis et al. 2018) leaving only 40% (McGlone 1983; McWethy et al. 2010) to 54% (Cumberland 1941; Perry et al. 2012) of the original forested area. European arrival in the early and mid-1800s (Molloy 1977) then led to the development of large-scale pastoral farming (O'Connor 1986). Forest removal resulted in significant soil erosion (McGlone 1989), similar to that which occurs in even indigenous forests after extreme rainfall events (Brown 1991). Remaining native forests are now governed by the Forests Amendment Act 1993, which has an indigenous forest policy, and logging of native trees is controlled by the Ministry for Primary Industries (Hawes and Memom 1998).

The indigenous vegetation of New Zealand had evolved without grazing mammals and without human disturbance. This resulted in a unique scenario where:

- Forests were vulnerable to grazing (as when deer, goats and possums were introduced to palatable forests)
- Native grasses were not adapted to mammal grazing despite bird grazing; and without 'stock camps' there was no transfer of nutrients to create fertile habitats for evolution of productive grasses
- There were few annual species in the flora indicative of a long-term perennial climate; and
- The mountainous landscape means only 14% of the land is suitable for ploughing and as a consequence animal grazing was, and is, the most productive way to utilise the majority of it.

In addition, New Zealand has only a few legumes among its native grasslands; the leafless broom of the genus *Carmichaelia* (broom) (NZ Rhizobia 2016) is an example and most are now in decline or threatened (Dawson 2016).

## Early plant introductions and the adaptation of introduced plant species

### *Conversion of forest to pasture*

The most dramatic transformation of the landscape occurred in the latter half of the nineteenth century when over half the remaining forest cover was removed (Guthrie-Smith 1969; Lancashire 1990; Arnold 1994; Knight 2009; Beattie and Star 2010). Forest removal continued at reduced pace until the end of the twentieth century (Ewers et al. 2006). Lowland forest that had not been felled or burnt was harvested to fulfil local and global demand for timber. Species such as cocksfoot (*Dactylis glomerata*) were introduced in the 1850s as a preferred grass to be sown into bush burn areas, through being hardier and more drought tolerant than ryegrass (*Lolium perenne*) (Rowarth et al. 1998). Most grass seed was imported from Europe until about 1880 when locally harvested seed reached sufficient quantities to supply domestic demand (Stewart 2006). The provision of cocksfoot seed was the beginning of what is now a successful forage seed production industry in New Zealand supporting domestic and international markets.

The clearance of bush over the last 200 years to establish an agricultural 'industry' follows the international pattern whereby forested areas are cleared to support an expanding population. This occurred in Europe between 500 and 900 AD and continues today throughout Asia and South America. The result is many formerly forested zones in the temperate and subtropical (and tropical) world have been cleared and 'pastured' with grasses adapted to the local conditions (Curtis et al. 2018). These pastures do not have a particular terminology other than 'high rainfall pastures' but could be included in the definition of mesic grassland (Ratajczak et al. 2014; Kalusová et al. 2017). In contrast, natural grasslands dominated in regions with rainfall below 600-700 mm. A meta-analysis combining a comprehensive list of European habitats and their species composition with a database of plant naturalisation records worldwide has shown that a broad habitat range, together with human-induced disturbance experienced in native-range habitats, can increase a species' chance of becoming naturalised in other parts of the world (Kalusová et al. 2017), including New Zealand.

The loss of indigenous forest cover in New Zealand has parallels in other regions. In Australia, Victoria had 88% forest cover in 1869 but this is now at 34% (Australian Bureau of Rural Sciences 2010). Similar statistics are available for all continents subjected to European settlement. Indeed, Britain after the last ice age gradually expanded its forest cover to what would be a maximum at 6000 BC. From 4000 to 2000 BC the onset of agricultural development coincided with large fluctuations in woodland composition and taxa (Whitehouse and Smith 2010). By 1000 AD England had only 15% forest cover which declined further to only 5% by 1900. Of note, Britain went through its expansion of pastures over the course of 6000 years, while in New Zealand it occurred in only 200 years. Further, the transplanting of European species, including livestock, to New Zealand was reliant on only a few adapted species (Goldson et al. 2020). As part of the transplant, they had to cope with the existing native flora and fauna, particularly in the soil microbiome (Attwood et al. 2019). Significantly the native flora of New Zealand has not contributed to the pastures, except for residual natural grasslands in drier regions. Attempts to develop a native grass seed industry has resulted in only one species, *Poa imbecilla* used for revegetation purposes (Stewart 2005).

Successful land development was based on adhering to four major principles: (a) using the correct fertiliser treatment to overcome soil fertility deficiencies and lime to optimise pH; (b) using perennial ryegrass and white clover (*Trifolium repens*); (c) preparation of suitable seedbeds to ensure establishment; and (d) controlled grazing management (Smallfield 1956). Re-establishment of pastures which had become unproductive, or sowing after cropping, also highlighted the importance of seedbed preparation, sowing depth, method of sowing, time and rate of sowing, soil fertility and grazing management on cultivable land (Brougham 1969).

There are many ways to partition New Zealand into vegetation zones from a grassland perspective, but three clear zones have emerged since the advent of pastoral agriculture:

(1) Maritime and temperate rainforest: ryegrass/clover-based pasture has predominated
(2) Semi-arid tussock grassland: dryland species, cocksfoot, white clover, sub clover (*T. subterraneum*), lucerne (*Medicago sativa*) are common; and

(3) Subtropical: kikuyu (*Pennisetum clandestinum*) and paspalum (*Paspalum dilatatum*) are significant.

At the first New Zealand Grassland Association conference held in 1933, Alfred Cockayne stated that

> "Following on the recognition that a rain-forest climate is synonymous with a high production grassland potential, an intensive type of grassland farming was evolved having for its objective the production and utilisation of milk producing pastures for the cow, ewe or sow – the essential elaborating machinery of our grass crop into butterfat and rapidly maturing meat" (Levy 1970).

This reinforced the fact that New Zealand's soils and climate were well suited to grassland farming.

It was recognised early (Connell 1933) that not all farms are equal. Farms that are essentially the same with respect to soil and climate can differ in carrying capacity by up to 80%. Hill country sheep farms of similar aspect and soil conditions can differ significantly in pasture quality and weediness. This difference was attributed to the gap between knowledge of how to advance grass farming and its general application in practice to achieve improved productivity. This realisation influenced the establishment of government sponsored technology transfer and advice through different consulting services within the Ministry of Agriculture after World War II (Te Ara 2008b). The government service was effectively abolished in 1990 and their role has been only partially replaced by private agribusinesses consultants. The latter tend to focus on financial advice and not all consultants are driven to find relevant and credible science. Analysis of the impact of Dairy Board consulting officers suggested that by all farmers using extension services, national dairy production would increase by 10% over 10 years, simply by improving methods of pasture utilisation (McKenzie 1980).

A key factor that improved grassland productivity was the phosphate revolution and use of lime (Langer 1977; Morton et al. 2005). The additions overcame nutrient deficiencies in native soils by increasing phosphate, sulphur and potassium fertility, which in turn enabled greater use of nitrogen-fixing clovers. Consequent improvements in soil nutrition have increased organic matter (Schipper et al. 2017) leading to improvements in the soil microbiome that contribute to more vigorous plant growth (Dignam et al. 2018, 2019). European earthworms (species of Lumbricidae and Megascolecidae) were also introduced (Lee 1961), although in many soils the species diversity of these is much lower than in European soils (Springett 1992). Native earthworms, of which there are 171 species, have a limited ecological range and live mostly in forests (Lee 1961). The lift in soil nutrition facilitated the shift from low fertility adapted species such as browntop (*Agrostis capillaris* syn. *A. tenuis*), *Danthonia decumbens*, crested dogstail (*Cynosurus cristatus*) and sweet vernal to more productive cocksfoot and then to ryegrass and white clover (Williams and Haynes 1990; Kemp and Lopez 2016).

## *Developments in seed and breeding*

The importance of plant breeding to develop grasses and clovers for pastoral agriculture in New Zealand was recognised by the 1920s (Gorman 1934; Saxby 1934). Prior to that seed germination testing laboratories were established which lifted the quality of seed being sold to farmers (Cockayne 1913). New Zealand was one of the first countries to develop a seed certification scheme (Crump 1985). Beginning in 1929, the aim was to provide confidence in germination rates and line superiority (Broadfoot 1990). In this way, inferior types were eliminated as uncertified. In this process, both grass and clover ecotypes were collected from many regions of New Zealand. The best of these local ecotypes was superior in production and persistence compared with overseas germplasm. A superior ecotype of perennial ryegrass was identified from Hawkes Bay as early as the 1930s (Saxby 1934) and in 1955 a derivative of this became known as 'Grasslands Ruanui' (Stewart 2006). The first white clover cultivar followed in 1964, known as Grasslands Huia (Caradus et al. 1995a). White clover had been categorised into six types based on leaf size, stolon density and production (Gorman 1934). Type 1 ecotypes, collected from Hawke's Bay and North Canterbury, were deemed superior. These had large leaves, widely spreading stout stolons and were highly productive and persistent.

### *The cost of pests and weeds*

The introduction and success of largely European plant species, adapted to grazing in conditions predisposed to rainforest, occurred in effectively all these regions of the world. However, and importantly, the local insect fauna and soil microbiomes differed across regions. These differences, and the introduction of various cohorts of insects (sometimes deliberately, but more often inadvertently), has had enormously damaging consequences for New Zealand's introduced pastoral systems (e.g. Goldson et al. 2020). Here it is estimated that the annual economic impact from the introduction of non-indigenous invertebrate pests ranges from $800 million to $2 billion (Goldson et al. 2005). The greatest impacts are caused by pasture nematodes (species of *Paratylenchus, Heterodera, Meloidogyne, Paratrichodorus,* and *Pratylenchus*) (up to $600 m/year) (Watson and Mercer 2000), Argentine stem weevil (*Listronotus bonariensis*) ($200 m/year), African black beetle (*Heteronychus arator*) ($242 m/year), and clover root weevil (*Sitona lepidus*) ($235 m/year) (Zydenbos et al. 2011; Ferguson et al. 2019). In addition, New Zealand pastures are badly impacted upon by the native scarab grass grub (*Costelytra zealandica*) causing losses of between $215 and $585 m/year, and a group of similar-looking porina moths (*Wiseana* spp.) that causes losses up to $170 m/year (Pottinger 1968; Ferguson et al. 2019). Lesser pests are also known to contribute to lost production. The transplantation of an incomplete ecosystem from Europe to New Zealand has led to disparity in many pests' natural enemies in terms of both numbers and ecosystem distribution. Related to this, there is a lack of biotic resistance to invasive species. In the evolved and complex ecosystems of Europe, such problems associated with ecosystem imbalance occur far less often with less intensity (e.g. Goldson et al. 2017, 2020). The regulated introduction of biocontrol options, both parasitoids and biopesticides, has been a strategy used over many decades with mixed success (Fernández-Arhex and Corley 2003; Hawkins and Cornell 2008; Tomasetto et al. 2017, 2018a, 2018b).

The introduction of European grasses and clovers, and in some instances forage brassicas (mustard, rape and turnips), also resulted in the arrival of a range of undesirable and weedy species. Plant species which can invade and form self-sustaining populations impacting on pasture production and quality total about 187, of which 180 are introduced (Bourdôt et al. 2007; Ghanizadeh and Harrington 2019). Deliberate introductions of plants such as gorse (*Ulex europaeus*), to mimic its use in the UK as fencing hedges and windbreaks, simply resulted in the release of noxious weeds (Worsley 1999). Other plants species introduced for horticultural and amenity purposes or use in home gardens have also become weeds after escape from cultivation (Healy 1952). Whether deliberately or unintentionally introduced the number of non-native plant species in New Zealand is now greater than native plant species (Hulme 2020). Based on the estimated annual cost of pastoral weeds, California thistle (*Circium arvense*) is considered to be the most important followed by meadow buttercup (*Ranunculus acris*), gorse (*Ulex europaeus*), nassella tussock (*Nassella trichotoma*), Chilean needle grass (*Nassella neesiana*), blackberry (*Rubus fruticosus*), broom (*Cytisus scoparius*), barley grasses (*Critesion* spp.), ragwort (*Senecio jacobaea*); nodding thistle (*Carduus nutans*); brier rose (*Rosa rubiginosa*), and hawkweed (*Pilosella* spp.) (Bascand and Jowett 1982; Bourdôt et al. 2007; Saunders et al. 2017). These species have been primarily managed using selective herbicides (Ghanizadeh and Harrington 2019), and grazing management (Hartley et al. 1978; Hartley and Thai 1979; Betteridge et al. 1994; Espie 1994; Popay and Field 1996; Tozer et al. 2011b), with biocontrol options used having limited success (Bourdôt et al. 2007; Fowler et al. 2010; Suckling 2013) (Table 1 Supplementary Information). The estimated costs of both weed-covered land reducing production and weed control is about $1.2 billion per year (Bourdôt et al. 2007).

## Pastoral agriculture in a foreign land – the opportunities and challenges

The advent of refrigerated shipping in 1882 provided the ability to transport frozen sheep and lamb carcases to the UK, encouraging the expansion of grassland areas throughout New Zealand (Cumberland 1941). Expansion was enhanced by the growth of dairy farming and the production of butter and cheese that could be transported successfully halfway around the world. As a result, from the late 1800s to the 1930s New Zealand was known as 'Britain's farm' (Reserve Bank of New Zealand 2007). This was further boosted by the wool boom associated with the Korean War in the early 1950s (New Zealand History Online), such that New Zealand was ranked among the wealthiest nations, with the income per-capita being 88% of that in the United States (Reserve Bank of New Zealand 2007), compared with 66% today. This was achieved despite slower development during the second World War when inputs such as fertilisers were reduced, there was shortage of labour, high prices for inputs such as seed, and paucity of supply of mechanised equipment and fencing (Saxby 1947).

As the demand for more agricultural exports grew, farmland expanded into more challenging landscapes and eventually into steep hill country in the North Island and the South Island high country (Hight 1979). The complexity of these additional systems created new requirements to understand their individual agronomic needs and productive potential. These issues have been comprehensively reviewed by Brougham (1981), Corkill et al. (1981), Cumberland (1981), Langer (1990), and Brooking and Pawson (2007, 2010).

While perennial ryegrass dominates New Zealand pastoral systems there is a place for other grasses. This includes: (a) annual (*Lolium multiflorum*) and hybrid ryegrasses (Easton et al. 1997); (b) tall fescue which is recommended for areas where summer growth and quality of ryegrass is reduced by moisture stress or high temperatures (Milne et al. 1997; Rollo et al. 1998); (c) cocksfoot particularly on low to moderate fertility hill country (Barker et al. 1999; Mills et al. 2006) and summer dry warmer areas (McCahon et al. 2021); (d) Prairie grass (*Bromus catharticus*) (Watkin 1974; Baars and Cranston 1977); and (e) Timothy, suited to cooler climates (Charlton and Stewart 2000).

There are advantages and limitations of introduced pasture species due to the severity of winter temperatures and summer droughts as well as grazing frequency and intensity. These effects are depicted in Figure 1. The figure demonstrates the utility of perennial ryegrass particularly when infected with *Epichloë* endophyte compared with other grass species. Also, of note are the particular adaptations of other species such as cocksfoot and lucerne to cold, dry environments.

In 1999, New Zealand had 109 cultivars from 23 different pasture species available through domestic and overseas suppliers (Charlton and Stewart 1999). Today there are over 150 certified cultivars available from these species. This choice ensures that there are species and cultivars adapted to the main ecoclimatic zones across a very diverse pastoral landscape. The use of superior ryegrass genetics on a typical dairy farm has been shown to be worth up to an additional $576/ha/year over the genetic base figure for ryegrass cultivars released before 1996 (Chapman et al. 2017). It has been estimated that the invested returns from animal production based on cultivated pastures can be more than 200% (Charlton and Belgrave 1992).

Sheep and beef systems on hill country are rainfed, ranging from 300 to 3000 mm per year, with feed largely coming from unimproved, but exotic resident species. These pastures are rarely renovated but rather maintained with superphosphate as the main fertiliser input (Journeaux et al. 2013; Schipper et al. 2017; Mills et al. 2021).

Efficient pastoral agriculture has resulted in significant and ongoing land use changes in response to the drive for profitability combined with government policies (Holden 1965;

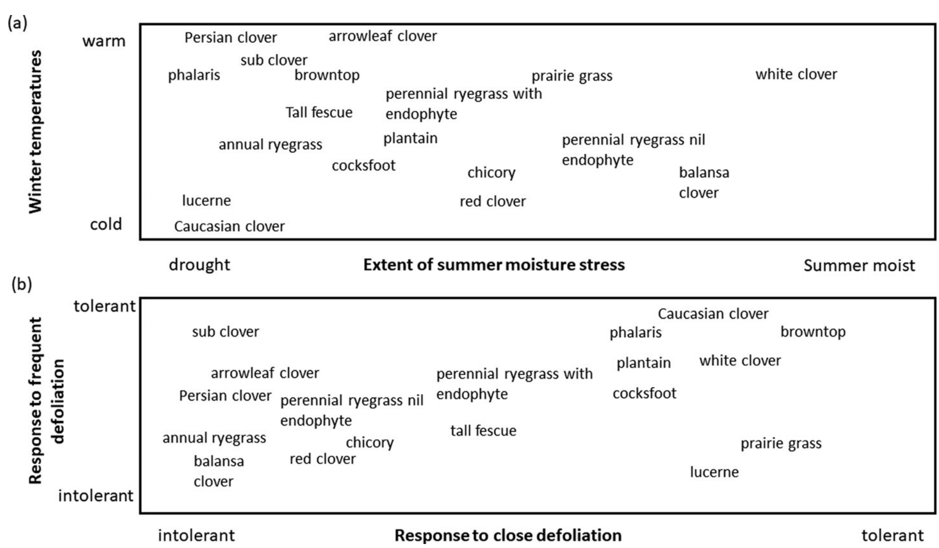


**Figure 1.** The estimated adaptation of pasture species to continuums of (a) winter cold, drought, and (b) frequency and intensity of grazing. Adapted and modified from Hoglund and White (1985).

Parminter 1991; Crofoot 2016). For example, in the 1970s there was rapid pasture expansion onto hill country areas that had previously been forested. This was driven by 1978 government incentives arising from supplementary minimum payments (SMPs) whereby farmers received a payment for the number of animals on their farm. This led to overstocking and deforestation of some areas of vulnerable land. The abrupt removal of subsidies a decade later resulted in the drive for high animal production profitability rather than sheer production. Sheep numbers have indeed declined since the 1990s, and while displaced from flat land by the dairy expansion, productivity has increased, and meat production levels maintained (Fennessey et al. 2016; Moot and Davison 2021).

Hill country areas have tended to be dominated by low quality grasses such as browntop that produce stolons or rhizomes leading to carbon-dominant thatch that reduces nutrient (particularly nitrogen) cycling. The appropriate use of oversowing, topdressing and grazing management on steep unploughable hill country the carrying capacity from 3.7 to over 11 ewes per ha (Suckling 1959). In response, hill country in those areas that can be cultivated has undergone some development via improved pasture grasses, legumes and herbs. However, this had the negative effect of leaving bare areas of soil vulnerable to wind and water erosion. Amongst other things, this led to the movement of phosphate into adjacent water ways. This problem was ameliorated through the development of no-till systems based on glyphosate applications that leave resident vegetation in place to bind the soil as new pasture seedlings emerge (Arnst and Park 1984; Chapman et al. 1985). Soil erosion and nutrient loss to waterways are more easily managed when the pastoral system is productive and profitable (Kemp and Lopez 2016). Therefore, glyphosate which has been used for direct drilling in both pasture and cropping areas for over 40 years, remains an important tool to reduce soil carbon losses to the atmosphere that occur routinely through conventional cultivation (Reicosky and Saxton 2006; McNally et al. 2017b). Recent headlines have suggested possible links to human health and its use has been discontinued in some jurisdictions. However, the scientific basis for adverse health effects continues to be challenged, along with the motives of those calling for its prohibition (Kuntz 2020), and recent evidence shows it is unlikely to move into groundwater (Close et al. 2021).

Native tussock grasslands have long been extensively grazed in their lower areas merging into mid-altitude steep-land in the South Island (McCaskill 1963). While it was primarily held that the 'sole use of such land was the feeding of livestock' (Saxby 1950), in the 1960s it became recognised that the tussock grasslands were also important for 'soil and water conservation in regulating stream-flow for livestock on the plains, for hydro-electricity, and irrigation' (McCaskill 1963). Rather than extend the ryegrass-white clover regime in cold tussock grasslands (Allan and Chapman 1987) it became recognised there was benefit in maintaining a large amount of standing vegetation to achieve watershed protection, organic matter accumulation and some form of production (Nordmeyer and Davis 1975; Hall 1987). A comprehensive guide to the use of pasture species in high country was published by Scott et al. (1995). The rate conversion of indigenous tussock grassland was almost 7000 ha per year from 1840 to 1990 (0.20% loss per year of remaining grassland); this decreased to about 3500 ha per year between 1990 and 2001(0.15% decrease per year); but increased to just under 5000 ha per year from 2001 and 2008 (0.21% decrease per year) (Mark et al. 2013). Early conversions to cultivated pasture were in lowland environments best suited for agricultural use (Newsome 1987). Many runholders on this land continue to be challenged with the prevalence of *Hieracium* (Hawkweed) weed species infestation (Steer and Norton 2013) and rabbit (*Oryctolagus cuniculus*) plagues (Scroggie et al. 2012), both impacting negatively on sheep productivity levels. Attempts to moderate these effects through the use of management to control *Hieracium* (Espie 1994) and the use of rabbit haemorrhagic disease to reduce rabbit populations (Norbury et al. 2002) have only been moderately successful.

## Plant and microbial technologies that support high performing and sustainable pastoral agriculture

Dairy, beef cattle and sheep farming in New Zealand is based on *in situ* grazing due to a favourable climate and soils combined with variously required forage supplementation via hay and silage and other of annual crops such as brassicas, fodder beet or maize. For dairy operations c. 30-40% of the operating expenditure is spent on feed and fertiliser (DairyNZ 2021a) highlighting the essential nature of plant-based technical developments that have been progressively integrated into the production systems.

The associated extensive plant- and microbial-based technologies that have had significant beneficial impacts on pastoral farming, are outlined in detail with appropriate references in Table 1 of Supplementary Information, include:

- Cultivar development through plant breeding across a range of species for improved annual and seasonal yield, persistence, nutritive value and feed quality, disease and pest resistance and seed yield. In addition, selection for adaptation to specific environments such as hill country or regional climatic extremes has also been the target of plant breeders.
- The use of legumes and herbs to improve feed and nutritive value of pasture.
- Use of specialist plant species for marginal land.
- Seed testing and certification to ensure reliable supply of high quality seed.
- Incorporating novel *Epichloë* endophytes into ryegrass and fescue for improved sward persistence and animal health and welfare outcomes.
- Improved biological N-fixation through use of effective rhizobium strains on legumes.
- Availability of biopesticides to manage damaging levels of insect pests.
- The introduction of beneficial insects such as pollinators and earthworms.
- Use of insect biocontrol agents to control weeds and pests.
- Chemical and biological herbicides used either directly or as seed coatings.
- Environmental plantings to manage health of rivers and wet-lands and improve soil conservation and nutrient leaching.
- Use of supplementary crops to fill feed gaps and improve spring/summer feed quality.
- Supplementary feed either conserved or imported to manage feed gaps.
- Management systems to optimise feed budgeting and improve pasture utilisation.

The adoption rate of these different developments has been high, particularly in the pursuit of profitability and/or productivity (Milne 2006a; Caradus et al. 2013; Lissaman et al. 2013). Importantly, effective extension activities directly by agricultural scientists and more latterly by agribusiness professionals have supported much of the adoption of these technologies and must be sustained to enhance farmer uptake and impart practice change (Gray et al. 2016).

### *Seed technologies*

The Plant Variety Rights law initially passed in 1973, and enacted in 1975 (Whitmore 1979), was a stimulus for commercial plant breeding and the gradual move away from government-funded and sponsored plant breeding activities (Paterson 1979). The history of forage plant breeding in New Zealand as it moved from introduced germplasm, to government sponsored breeding and then on to the private sector has been well described by Smith and Mather (1985). Commercial seed production processes and technologies to deliver a high quality and cost-effective product to farmers have been developed and refined over many years for all of the important, and of some more minor pastoral species (Rolston and Clifford 1989; Rolleston 2016) (Table 2 – Supplementary Information) but remains a challenge for more niche species (Monk et al. 2016). Improvements in seed production leading to higher yields per ha and improved seed quality, outlined in detail with appropriate references in Table 2 of Supplementary Information, include for:

- Annual and perennial ryegrass – appropriate plant density, use of nitrogen, weed control and use of growth regulators and fungicides.
- Tall fescue – appropriate plant density and use of nitrogen.
- Epichloë containing grasses – careful use of fungicides; low seed moisture content at harvest; treat seed infected with selected endophyte as a high-value perishable product.
- Cocksfoot – use of phosphorus and potassium.
- Prairie grass – use fungicide treated seed, use appropriate plant density and use of nitrogen and avoid grazing.
- Phalaris – no defoliation between sowing and harvesting; correct harvest time to avoid seed shattering.
- White clover – appropriate row spacings and sowing rate, avoiding overgrazing, close mid-November, harvest 1 month from main flowering, provision of bee hives, and appropriate irrigation.
- Red clover – reduce paddock size to improve pollination, close after early December, harvest March or early April.
- Lotus pedunculatus – spring sowing; herbicides to control clover; harvest when 70-80% of pods turn brown.
- Lucerne – low seeding rates, early sowing, good early weed control; use of alkali and leaf cutting bees.
- Chicory – time of closing, seed development, response to nitrogen, herbicide tolerance and methods of harvesting.
- Brassica – isolation distances within pollination groups for both insect and wind pollinated species.

## Management and soil-associated technologies that underpin pastoral agriculture

### *Pasture renewal and renovation*

Regular pasture renovation is an effective on-farm strategy to increase pasture yields. Compared with old pasture, this can amount to over 40% in the first autumn-to-spring period and then by 24% in subsequent years (Chestnut 1986). Some of this is due to the benefit of plant improvement which has been estimated to have added $12–$18 per ha per year (depending on region) operating profit on dairy farms since the mid-1960s (Chapman et al. 2017). It has been estimated that on dairy farms a 10% increase in dry matter yield due to pasture renewal has the potential to increase annual on-farm profitability from $271/ha to $478/ha (Brazendale et al. 2011). Glassey et al. (2010) demonstrated a yield advantage of 4% and feed quality advantage of 7%, contributing to the additional profit of more than $900/ha/yr. However, despite gains in pasture yield and quality with establishment of new pastures on dairy farms, pasture renewal rates have remained low – at about 6–8% p.a. (Sanderson and Webster 2009) and only 2–3% p.a. for sheep and beef (Caradus 2006). A 2010 survey of Waikato and Bay of Plenty dairy farmers has shown that they were more certain about pasture renewal decisions than about which cultivars or endophytes to use (Kelly et al. 2011). Various models have shown the payback period for pasture renewal is between 2 and 3 years on dairy farms (Stevens and Knowles 2011; Fraser et al. 2016). Sowing practices to ensure successful pasture establishment have been reviewed for both dairy (Thom et al. 2011) and non-cultivatable sheep and beef grazed hill country (Tozer and Douglas 2016). Decision-making about when and how to renew pasture can often be subjective but needs to be more informed via data to achieve the optimal gains through cost:benefit analysis (Kerr 2020).

Concerns by farmers that pasture renewal benefits are at times not realised (Kelly et al. 2011; Tozer et al. 2011a) have been examined by comparison of renewed and unrenewed pastures over a 5-year period (Tozer et al. 2015). Renewed pastures produced on average an additional 1.73 T DM per year over the first 3 years with a greater contribution of clover, sown grasses and unsown grasses and a smaller contribution of broadleaf weeds. In addition, the abundance of invertebrates was lower in renewed than resident pastures in some years. With the estimated cost of pasture renewal being $1300 per ha, an additional 6.5 T DM per ha would be profitable on most farms.

Success of pasture renovation can be improved using herbicides, sub-division, grazing management, appropriate fertiliser (Macfarlane and Bonish 1986), and use of salt in some circumstances (Gillespie et al. 2006), as well as using certified seed (Charlton 1991). On unploughable land the use of stock treading, while not as effective as herbicide, has been beneficial in promoting seedling establishment (Sithamparanathan et al. 1986). The development and use of direct drilling/seeding technologies practised as no-tillage and reduced tillage offer an additional dimension for sustainable agriculture globally in both seed industries and general food production (Stevens et al. 2000).

### *Managing feed quality*

Pasture quality parameters that improve feed intake and nutritive quality are major determinants for improved liveweight gain, milk production as well as animal health and reproductive performance (Lambert and Litherland 2000). The two most commonly used measures of nutritive value are digestibility and metabolisable energy levels (Ulyatt 1970). Nutritive value is influenced by pasture species composition, and the age of pasture and the amount of dead matter present, plus the negative impact of some environmental factors such as high temperature, fertiliser imbalances, and extremes of soil moisture levels (Waghorn and Clark 2004). The inclusion of forage legumes and herbs is known to improve feed quality compared with grass monocultures (Golding et al. 2011). Forages which contain compounds such as condensed tannin can improve animal growth rates and health (Min et al. 2003; Waghorn and McNabb 2003; Woodward et al. 2004; Waghorn 2008), while other compounds such as ergovaline (Caradus et al. 2020) and lolitrem B (Lane 1999) from some *Epichloë* endophyte strains found in grasses can be detrimental. Effective novel endophytes which do not produce concerning levels of mammalian toxic secondary metabolites are now available (Caradus et al. 2021).

### Grazing management through subdivision and electric fencing

The grazing management strategies available to New Zealand farmers have developed through extensive subdivision, resulting in improved feed budgeting and pasture use as well as reduced labour costs (Squire 1986; Jones 1988). Improved catchment management, water quality and reduced soil erosion has also been achieved (King 1969). In addition, subdivision has allowed the use of specialised pastures (Brown and Green 2003), effective management of spring feed surpluses (Lambert et al. 2000), and accommodation of differences between aspects/topography in hill country (Grant and Brock 1974; Lambert 1976). The ability of hill and high-country farmers to match pasture supply and quality to appropriate classes of livestock has enhanced on-farm productivity despite declining ewe numbers (Cocks et al. 2002; King et al. 2016; Stevens et al. 2016; Moot and Davison 2021). For dairy, grazing management principles for ensuring production and pasture persistence are well known (MacDonald et al. 2011). The developments have also coincided with improved weed control management (Rolston et al. 1982), and pasture establishment (Gillespie et al. 2006). Paddock subdivision *per se* is not, however, a panacea for poor on-farm management (Parker and McCall 1986). The use of electric fencing began over 80 years ago; the concept started in the USA but was quickly adopted, developed and manufactured in New Zealand, revolutionising management flexibility (Jones 1988). The advent of virtual fencing will further minimise fencing costs and increase flexibility of animal management (Brier et al. 2020).

### Feed budgeting and pasture growth rate models

The development of models for understanding farm systems and to assist with decision making on-farm began in the 1970s and 1980s. Models were based on pasture growth rate data routinely collected by government agencies (e.g. Radcliffe 1974a, 1974b; Radcliffe 1975; Rickard and Radcliffe 1976; Morton and Paterson 1982; Roberts and Thomson 1984a, 1984b). The trends derived from these data continue to be used by farmers and consultants to develop feed budgets and for feed provision planning, particularly in times of drought or adverse weather events. Computer modelling has improved the prediction of pasture production with relatively few environmental inputs such as on-farm rainfall and temperature (Mills et al. 2021). These have resulted in decision-support tools such as the Pasture Forage Forecaster (DairyNZ 2021b), and Farmax which provides a planning and budgeting tool to test the commercial and biological feasibility of different land-use and management scenarios on farm (Farmax). The models have been largely based on ryegrass and clover mixed swards, with new equations provided for lucerne (Moot et al. 2021b). There remains a need to develop further components for other species, such as red clover and plantain. A central repository to consolidate the years of formal and informal data collection and allow the development of model components has recently been developed (Lincoln University; Moot et al. 2021a).

### Pasture measurement techniques

The provision of information for feed budgeting requires reliable measurement of variations in pasture production, both annual and seasonal, across a range of scales from paddock, to farm and region (McNeur 1953; Cochrane 1976). This process can be laborious and so a variety of methods have been developed to expedite this task which are outlined in detail with appropriate references in Table 3 of Supplementary Information. These employ both direct and indirect measures and vary in terms of reliability, accuracy and ease of use and affordability. Direct measures include cage and trim technique, possibly using a mower or hand clippers to a constant height, by taking random quadrats. Indirect measures include:

- Visual assessments.
- Pasture height.
- Capacitance metre.
- Weighted disc/rising plate metre.
- C-DAX rapid pasture metre.
- LIDR – Light Detection and Ranging.
- Aircraft photography using colour and panchromatic photography or multispectral cameras
- Satellite imagery using multispectral scanners
- Hyperspectral imaging
- Fixed invisible near-infrared light sensors
- Photogrammetry

### Technologies for measuring and managing soil and water conservation

The instability of up to 40% of New Zealand landscapes (Gibbs 1963), particularly steep hill country with shallow soils, has been long recognised (Cumberland 1947; Wilkie 1954; King 1969; Tran et al. 2020). In 2008, this was estimated to cost the New Zealand economy $157 million per year (Jones et al. 2008). The list of methods and technologies to manage both soil and water conservation is extensive. It includes planting trees (McGregor et al. 1999; Wilkinson 1999; Douglas et al. 2013), grazing management to stop fragile soil over-grazing., inappropriate stock class use (e.g. heavy animals on wet steep hill country) (Hicks et al. 2011), cultivation confined to easy contours (Basher 2013), fencing and riparian planting along waterways (to trap sediments and nutrients) (Bewsell et al. 2007; Daigneault et al. 2017), water management through using artificial channels to direct water flow and the use of dams to manage debris and water flow (Gregg 2008). Additionally, dense vigorous pasture cover will reduce sheet, rill and wind erosion but, largely because of the shallow root systems, the pastures will not prevent slips and slumping (Blaschke et al. 1992; Basher 2013).

Protecting soils during wet winters, particularly on dairy farms, has led to several off-paddock facility developments (Longhurst et al. 2006a, 2006b), thus allowing the removal of animals from pasture when it is prone to treading damage. These innovations can lead to reduced overland flow of water and nutrients, less nitrate leaching and lower greenhouse gas emissions on poorly drained soils (van der Weerden et al. 2017). Cost-effectiveness continues to be under debate (Laurenson et al. 2017), but depends on type of facility, climate, soil type and, of course, what factors are modelled.

A range of soil and water conservation managed Environmental Farm Plans have continued to be applied voluntarily (Manderson et al. 2007; Cameron 2016), but they have recently become a regulatory requirement (Ministry for the Environment 2020) managed by Regional Councils. Their success in achieving world excellence in environmental management is contingent upon plans being farmer-centric, farmer-owned and adding value to their business (Stokes et al. 2021) but is likely to require further scientific research.

### *Irrigation*

From 2002 through to 2019 the area of irrigated agricultural land in New Zealand increased from 384,000 ha to 735,000 ha (Stats NZ 2021a), which is 2.75% of New Zealand's total land area of 26.7 million ha (of which about half is farmed) (Stats NZ 2021b). Irrigated pastureland is now 16% dairy compared with 2% each for sheep and beef. The largest irrigation schemes were developed in Canterbury in the late 20th and early 21st centuries (Young et al. 2004), although the first recorded irrigation system in Canterbury was constructed by a Wakanui farmer, Joseph Hunt, in 1878 (Lobb 1968). Initially, the 'wild-flood' irrigation schemes of Central Otago were derived from previous water rights obtained for gold sluicing in the 1880s (Heiler 2008). While in Canterbury irrigation trials started in the 1880s, large scale irrigation border dyke systems did not start until the 1930s (Taylor 1974; Taylor et al. 1985). These have been now largely replaced by overhead pivot or lateral irrigation technology (Evans 2004; Pangborn and Woodford 2011; Saunders and Saunders 2012). In 2007, irrigated land nationally (about 4%) contributed about $1 billion per year (Le Prou 2007), and by 2012 this was estimated to be $2.17 billion (NZIER 2014).

The often-inefficient designs of early irrigation schemes have been resolved with improved designs and increasing water use efficiency (Taylor et al. 1985). However, to manage irrigation water efficiently farmers need to measure and monitor irrigation application depths and uniformity (Thomas et al. 2006). Advances in precision and variable rate irrigation have reduced water use, reduced nitrate loss and decreased energy requirements (Hedley et al. 2009; McDowell 2017).

### *Fertiliser – superphosphate, mineral nitrogen and lime*

On most New Zealand pastoral lands, soil science research has guided the use of both phosphorus and sulphur to improve pasture quantity and quality (Daly et al. 1999; Roberts and White 2016). These nutrients are applied to encourage the legume component which also requires lime to ensure the pH is >5.5 for micronutrient availability for plant uptake (Widdowson and Walker 1971). Specifically, molybdenum is essential for effective N-fixation of legumes and reduction of nitrate as a step towards protein synthesis (Sherrell and Metherell 1986). In New Zealand, deficient levels of molybdenum were first discovered through investigation into a disease of cauliflowers termed 'whiptail' (Davies 1952), managed by the application of small quantities of ammonium molybdate (Mitchell 1945; Sherrell and Metherell 1986). On cultivatable land it is recommended that lime be used after correcting for other major nutrient deficiencies (Edmeades et al. 2016).

Aerial top dressing, first trialled in 1949 (James 1984), has been viewed as synonymous with successful hill country development (Tebb 1959). Improved returns can still be achieved through new technologies that allow the application of fertiliser at variable rates to match the growth potential of contrasting hill country zones (Gillingham et al. 1984, 1999; Roberts and White 2016). Further work is required to improve the accuracy and precision of differential rates of application (Chok et al. 2016) and is the subject of considerable research (e.g. Yule et al. 2015).

Large amounts of seed and fertiliser were applied to unploughable steep hill country from the 1930s (Smallfield 1938) with the best establishment of introduced clovers occurring in early autumn (Suckling 1951). Applications of phosphate were most effective when applied after the seedlings were well-established.

Nitrogen is the main limitation to pasture production (Carran 1978; Mills et al. 2006) and has therefore become the main fertiliser used to drive pasture production in dairy systems (Moot et al. 2020). This is particularly the case for irrigated areas, while in rain-fed regions nitrogen is used more as a tactical tool to meet short term deficits in the shoulders of the season (early spring and late autumn). Prior to the 1990s, the predominant source of nitrogen in pastoral ecosystems was through companion clovers (Ball 1969; Brock et al. 1989). Analysis in the 1980s concluded that use of high rates of nitrogen fertiliser (> 80 kg N/ha) was unlikely to be profitable on dairy farms (Buxton 1981; Bryant et al. 1982; Holmes 1982). However, with the advent of cheap synthetic mineral nitrogen fertiliser and the increase in the value of milk solids there was a major shift to its use in the 1990s. This coincided with the arrival of clover root weevil (*Sitona obsoletus*) that led to an even greater reliance on synthetic nitrogen (Mills et al. 2006). Rates of up to 400 kg/N/ha and irrigation have enabled stocking rates to increase to 3.47 cows/ha resulting in an increase of average herd sizes to 810 cows, compared to the New Zealand average of 2.84 cows/ha and herds of 415 cows (DairyNZ 2021a). Nitrogen application resulted in predictable pasture growth over short time periods which, for a dairy farmer, was able to be captured as milk 'in the vat' and therefore improved on-farm profitability (Barr 1995). Combining the advantages of clover in terms of per cow performance (Harris et al. 1997, 1998) and nitrogen for increased dry matter production was considered possible at up to 200 kg N applied/ha/year if the additional pasture was utilised in spring to maintain clover content (Harris and Clark 1996) and stocking rates or conservation polices were modified to use the additional feed (Harris et al. 1994).

Similarly, for sheep farming, the use of synthetic nitrogen in late autumn was found to provide a 14% increase in weaned lamb liveweight (Lambert and Clark 1986). On dry hill country, over a 7-year period, the use of nitrogen at 30 and 50 kg N/ha/year applied in early to mid-winter resulted in increases of $30/ha and $50/ha compared with no nitrogen applied (Gillingham et al. 2004). The key is to maximise pasture use through increased stocking rates (Luscombe and Fletcher 1982) during the period of reliable soil moisture and pasture growth conditions in the winter/spring. On dryland, yields of cocksfoot increased from 6.5–16 t DM/ha/year with the application of synthetic nitrogen (Mills et al. 2006). Response rates of over 20 kg DM/kg of applied nitrogen have been recorded in hill country pastures (Luscombe 1979; Lambert and Clark 1986; Gillingham et al. 1999; Fasi et al. 2008), which points to severe nitrogen deficiency. On higher fertility dairy pastures, a response of less than 20 kg DM/ha per kg N applied can be expected (Glassey et al. 2013). However, with nitrogen fertiliser application a significant reduction in clover content can occur (Luscombe and Fletcher 1982; Harris et al. 1994; Harris and Clark 1996).

### *Impacts of mineral deficiencies in NZ pasture on animal health and production – Co, I, Se, Cu and Na*

Many New Zealand soils have low natural levels of essential trace-elements, e.g. selenium, cobalt, copper and iodine, all of which are required for healthy animal production (Grace and Clark 1991). This can be remedied by topdressing the pasture, oral dosing and/or injections (Grace 1992). Low levels of selenium affect up to 30% of New Zealand's agricultural area (Grace 1994; Grace et al. 2011). This is not required by plants, but selenium blood concentrations and production responses by grazing animals have been positively correlated (Wichtel 1994; Wichtel et al. 1994). Supplementation options include drenches, injectable products, slow release intraruminal boluses or selenised feed additives designed for farms with extensive grazing and/or low stocking rates (Metherell et al. 1996). However, it has been demonstrated that the direct application of selenium (usually with fertiliser) to intensively grazed pastures is a highly effective long-term strategy (Watkinson 1989; Moorhouse et al. 1999; Grace and West 2006).

Cobalt is important in the synthesis of vitamin B12 in the rumen. Cobalt deficiency in animals is usually associated with specific soil types, including the pumice soils of the North Island and granite soils of Nelson (Andrews 1955). Cobalt topdressing of affected land has become an accepted practice (Metherell 1989; Hawke et al. 1994).

Iodine deficiency has been a feature of New Zealand soils and can result in impaired reproduction and perinatal mortality of both sheep (Sargison et al. 1998) and cattle (Mee et al. 1995). Even recent surveys have shown that iodine concentrations in 26% of pastures were insufficient for sheep nutrition, and 87% of pastures for cattle nutrition (Jensen et al. 2019). Management of iodine deficiency has been through direct animal treatment (Grace 1992) but the use of iodine fertiliser to pastures can lift herbage iodine concentrations to acceptable levels (Smith et al. 1999), although this has not been applied in practice.

Copper deficiency can cause nerve and bone disorders in lambs, and poor growth and reproductive problems in cattle and can be exacerbated by high molybdenum levels in pasture (Grace 1969). The application of copper through fertiliser and by licks can eliminate these issues for both sheep and cattle (Cunningham 1944), but copper boluses are more commonly used in dairy animals and deer, where required.

Sodium, an essential element for both animal health and production, can be at low levels in some regions of New Zealand (Edmeades and O'Connor 2003) particularly those regions inland from the coast (Suttie 2010). Treatment of suspected sodium deficiency can be through NaCl oral drenching, water trough treatment, salt licks or fertiliser Na applications (Edmeades and O'Connor 2003).

## Balancing the benefits and the risks for future pastoral agricultural successes

Pastoral agriculture in New Zealand faces several challenges and opportunities that will require continued research and development to provide effective solutions. Over 20 years ago (Campbell-Hunt 1997), these were summarised with four scenarios which still have relevance (Figure 2). In the overview, strategies A and B represent resource intensive farming, commodities, cost leadership and process efficiency, while strategies C and D reflect high product differentiation, product leadership and customer alignment (Parker 2001). The differences now in comparison with the operating environment for pastoral agriculture 20 years ago are increased regulation, increased consumer demand for sustainable and ethical production systems, and increased economic pressures on farmers.

A global food system mass balance model (Sustainable Nutrition Initiative) has been used to predict the nutrition available to the average global citizen both now and in the future. This model focuses on global nutrient requirements, not demand, and even so, identifies large gaps in available levels of some crucial elements such as calcium and vitamin E (Smith et al. 2021). This analysis indicated that with the demand to move more towards predominantly or entirely plant-based individual diets, to nourish the entire global population sustainably, there will be a shortfall of several nutrients. Both animal and plant foods provide essential human nutrients and emphasis should be placed on diets remaining plant-based but optimised by supplementing with animal-based food (Coles et al. 2016).

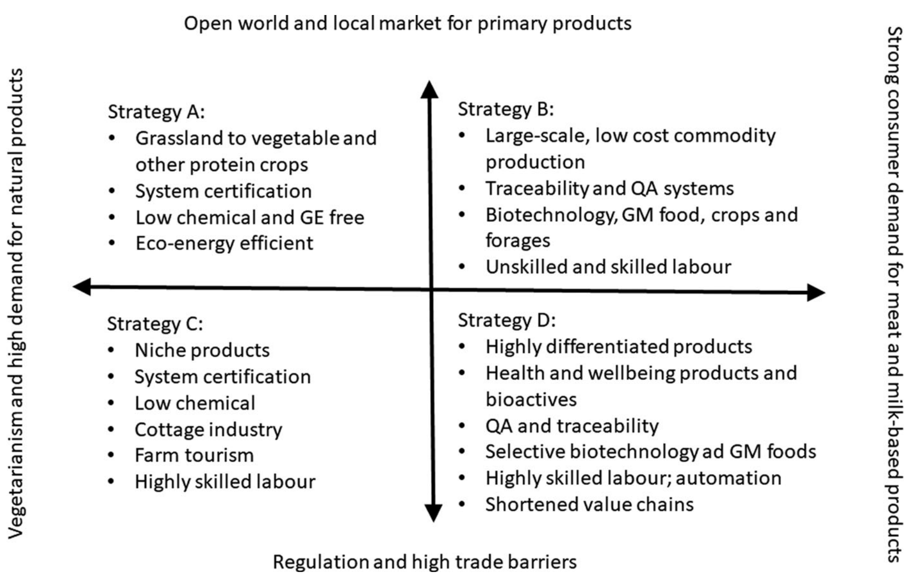


**Figure 2.** Four possible future scenarios for New Zealand grassland (Campbell-Hunt 1997 – with permission).

## Consumer and market demands

### Sustainable food production

Consumers are demanding sustainable practices in food production. Within this context grassland systems such as used in New Zealand are considered natural, but they can require significant inputs to maintain production. Expectations have emerged for low carbon emission farming, increased awareness of soil issues, ecosystem biodiversity, improved water quality and fact-based approaches to animal welfare (Robert Erhard – Nestle, pers. comm.). Much of this can be achieved by matching feed demand of the herds/flocks with the annual and seasonal pasture supply profile and using pasture species best suited to the predominant climate (Horan and Roche 2020). Both options are well understood by researchers and well within the scope and capability of New Zealand grassland farmers through effective pasture management. Returning to legume-based pastures, maximising the use of biological nitrogen fixation, and displacement of the need for synthetic nitrogen fertiliser will be important, as has been advocated by the science community for the last 25 years (Caradus et al. 1995b; Moot et al. 2003; Cosgrove 2005; Woodfield and Clark 2009). The return to legumes has also been recently recognised in Ireland, another pastoral agricultural economy reliant on grazed grass systems (Delaby et al. 2020).

### Protection of indigenous vegetation

Consumers are also asking for assurances about maintenance of remaining indigenous vegetation. Lowland remnants of indigenous vegetation are valued for their inherent (including aesthetic) value, and many landowner farmers have protected them by pest-excluding (vertebrate) fencing and removing some from grazing systems altogether (Smale et al. 2008; Dodd et al. 2011; Innes et al. 2019). This can improve soil conservation and biodiversity protection leading to landscape and ecological enhancement. However, New Zealand society at large has often ignored the goodwill of landowners in doing this work rather than supporting and nurturing it (Palmer 1999). Restoration of New Zealand native ecosystems must address the factors that limit natural regeneration, the options for large-scale plantings, and calls for eco-sourcing ecologically appropriate plant species and mycorrhizae, the establishment of certification for native seed and seedling supply, and the adoption of best-practice planting and early seedling management (Norton et al. 2018). The QEII Trust has been active for over 20 years in assisting farm owners in protecting remnant native vegetation (Scrimgeour et al. 2017).

### Managing the environmental impacts of intensification

Ongoing intensification of New Zealand agricultural systems has the potential to threaten the environment, sustainability, and reputation of agricultural production. Technologies and systems that promote sustainable land-use that ensure resource use is sensibly integrated with conservation have been proposed as a solution (Moller et al. 2008). Interestingly, from 1990 to 2014, despite dairy intensification and increased use of nitrogen fertiliser, visual clarity of rivers improved in 35 of 77 catchments due largely to dairy cattle exclusion from rivers through riparian planting and fencing, and due to the significant decrease in sheep numbers from 58 million sheep in 1990–31 million in 2012 (Julian et al. 2017). However, nitrogen has significantly increased in 27 of 77 catchments, attributable directly to increased cattle density and legacy nutrients built up since the 1950s that continue to leak slowly into the rivers.

Nitrate is a naturally occurring compound readily taken up by plants as their main source of nitrogen; it is the main nutrient that limits plant growth. Nitrate leaches from all agricultural systems, primarily from urine patches (Hoogendoorn et al. 2010) exacerbated by increases in soil pH when urea hydrolyses to ammonia which in turn increases transformation of $NH_4^+$ to $NH_3$ (Curtin et al. 2020). Ammonia and nitrous oxide volatilisation also occurs from both urine patches and applied fertiliser which can result in losses of up to 40% of applied nitrogen (Sherlock et al. 2008). For a time, dicyandiamide (CDC) a nitrification inhibitor was applied to mitigate this effect (Di and Cameron 2002) but has been withdrawn due to residue contamination issues in milk (Welten et al. 2016).

As agricultural production has increased with the expanding human population so has the opportunity for nitrate to leach (Addiscott 2005). In New Zealand, new regulations have capped nitrogen fertiliser application at 190 kg N/ha/year (New Zealand Government 2021) due to leaching into lowland streams, particularly in Canterbury, Manawatu and other intensive dairying areas of the country. Additionally, with a combination of stock exclusion from waterways, riparian protection, and nutrient and effluent management, it has been estimated that losses of nitrogen, phosphorus and sediment to water can be reduced significantly by 34, 29 and 66%, respectively (McDowell et al. 2020; Monaghan et al. 2021a, 2021b). Although concerns about nitrate and health have been raised, a recent review has determined that less than 10% of nitrate exposure in New Zealand was from drinking-water and concluded that it is highly unlikely that nitrates in drinking-water or the diet present an increased risk of cancer (Cressey and Cridge 2021).

Currently, the most topical environmental impact of pastoral agriculture is its contribution to New Zealand's total greenhouse gas emissions. New Zealand has ratified the 2016 Paris Accord, under the auspices of the United Nations Framework Convention on Climate Change (Mfe 2016). The expectations from this agreement are that New Zealand will reduce emissions to 30% below 2005 levels by 2030 (National Interest Analysis 2016). New Zealand has a unique emissions profile globally, linked to its reliance on agriculture for export income. This contrasts with the country's low population and the high proportion of energy production from non-fossil fuel sources (especially hydroelectric). While efficient grazing strategies and improved forage quality mean New Zealand dairy and meat have low water and carbon footprints per unit of product, the recent Climate Change Commission report (Climate Change Commission 2021) requires that methane emissions be reduced by 12% by 2030, and 24–47% by 2050, compared with the 2019 emission levels. Methane is produced naturally through the breakdown of plant material by micro-organisms in the rumen. Internationally, the New Zealand livestock industry is leading the search for mitigation strategies to reduce emissions from livestock and minimise nutrient losses (Ministry for the Environment 2021). Current work, suggested as 'needs' and identified a decade ago (Clark et al. 2011), include the development of methane inhibitors, selection of low emitting animals, and/or introduction of compounds that reduce methane emissions, e.g. 3-nitrooxypropanol (3-NOP) (Duin et al. 2016). While the research continues, farmers have made significant on-farm changes leading to reduced emissions. Indeed, the sheep and beef sector have reduced emissions intensity by 30% since 1990 from ~1.0 to 0.7 kg $CO_{2e}$/kg product and are credited with having low emission levels per kilogram of product produced (Ledgard 2017; van Selm et al. 2021). This is laudable in terms of providing agricultural products with lower emissions, but it does not necessarily contribute to attaining the total emissions reduction, in absolute amounts, that New Zealand has committed to under the Paris accord.

Further offsets in greenhouse gas emissions from pastoral agriculture will come from on-farm planting of woody vegetation to exclude stock from waterways (riparian planting), for erosion control or to retire unproductive land. Total planting stands at about 2 million hectares on hill country, which Ministry for the Environment estimates will offset at least 30% (Ministry for the Environment 2021) of the total sheep and beef emissions. However, for the proposed tree planting driven by an emissions trading scheme, to leave a positive legacy it will be important to plant the right tree species in the right place, with a preference for native species on steep hill country (ICAP 2021).

### *On-farm productivity and profitability*

On dairy farms, operating profit from productivity (PFP) is the difference between actual operating profit and the operating profit that would have occurred with no productivity changes since a base year (Figure 3). The main contributory components of PFP are milk solids production increases since the base year, operating expenses savings in inflation adjusted terms since the base year, and end-of-year operating profit per kilogram milk solids (influenced by milk prices). DairyNZ and dairy farmers must increasingly focus on achieving cost-efficient milk solids production and PFP provides a means for monitoring the value of productivity gains over time. However, the volatile nature of PFP

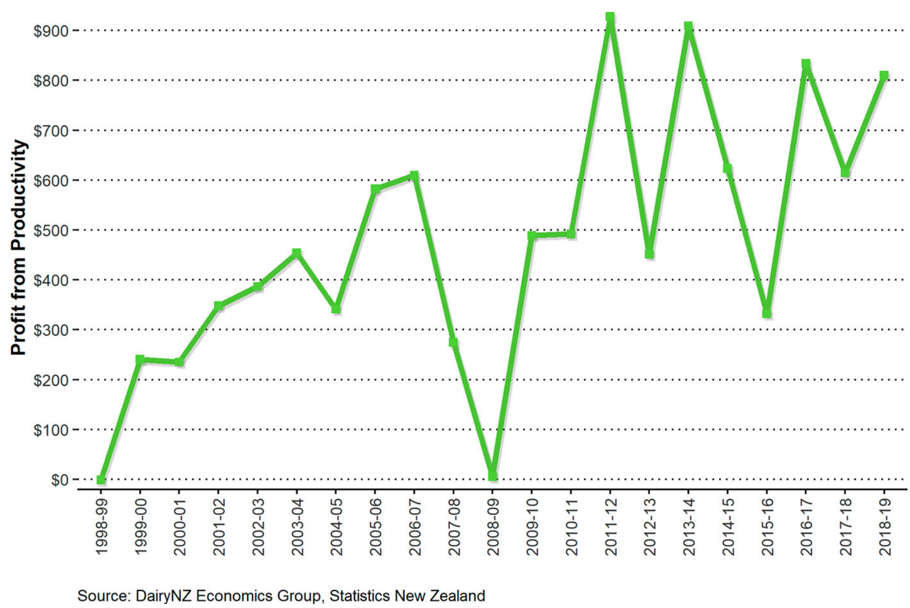


**Figure 3.** Profit from productivity gains for dairy from 1998/99 (sourced with permission from DairyNZ Economics Group, DairyNZ 2021a).

(Figure 3) is caused by fluctuations in both milk prices and seasonal rainfall, both of which are largely outside the control of dairy farmers.

Similarly, for sheep and beef farmers, profitability is at the centre of decision-making when considering changes in management and uptake of new technologies. Farmers need to understand and have the confidence to make changes which in the future will include supporting a community with a rewarding working environment and lifestyle. This will involve improvements in productivity (i.e. more output with the same, or lower physical inputs), managing external pressures especially with the environment (e.g. riparian management and water quality) which will increase compliance costs, and satisfying new markets with a greater spread of product supply off-farms (Fennessey et al. 2016).

### *Future research and development requirements*

A review of scientific and technological advances in pastoral agriculture based on publications in the New Zealand Grassland Association conference proceedings over 75 years concluded that 'New Zealand's international competitive advantage in producing agricultural products will be maintained through the ongoing application of innovative technologies and smart business practices leading to an increase in on-farm efficiencies, productivity, and added value' (Caradus 2006). The same still applies today, where research and development investment is a prerequisite for continued improvements in pastoral agricultural productivity (Caradus 2007) and environmental sustainability. This will require:

(1) Development of new technologies and their uptake by farmers to improve productivity, biosecurity, feed supply options, environmental integrity, energy use efficiency, and the opportunity to create new added-value products
(2) Maintaining high objective standards of scientific integrity and scrutiny
(3) Providing opportunities for debate and interaction within the interested community, viz. farmers, extension specialists, agribusiness, policy advisors and makers, regulatory managers, and scientists.

### *Biological-based solutions*

Regenerative agriculture has been advocated predominantly by NGOs and the media as part of a long running debate between sustainable intensification and agroecological approaches (Giller et al. 2021). Agronomists contend that current and existing conventional systems can deliver low environmental impacts per unit of food produced or in some cases per hectare (Rowarth et al. 2020). The emphasis remains to continue to develop improved or new systems that leverage existing knowledge to provide food while minimising environmental impacts. The integration of biologically-based solutions, such as those being promoted by Attwood et al. (2019) with the 'biome' approach, as a means of removing the use of synthetic chemistry, to aid control of pests and diseases, improve nutrient uptake, and stimulate plant growth must be options explored through well-funded research, and delivered to farms for commercial advancement. For example, root arbuscular mycorrhizae are known to be beneficial for legume establishment and growth (Crush 1978; Crush and Caradus 1980) particularly in phosphorus-deficient soils (Crush 1973; McLachlan et al. 2021). However, there have been few studies resulting in practical applications from such symbiotic association in New Zealand's mixed-species pastures, despite considerable effort (Powell and Bagyaraj 1984). Selection of host plants with a propensity to form effective mycorrhizal associations is an opportunity (Crush and Caradus 1980) and should be a priority for application in low fertility soils. In general, to improve agricultural output and sustainability, plant breeding methods to optimise the symbiotic benefits of incorporating beneficial microbes into crop and pasture species is required (Caradus and Johnson 2019), in addition to an improved understanding of the importance of soil microbial communities.

Over a decade ago, research on increased use of alternative and/or new grasses and legumes as complements, or substitutes, for ryegrass and white clover was indicated as required particularly in response to changing climate and land use pressures (Williams et al. 2007). This is yet to occur. In addition, the germplasm base of most pasture species used in New Zealand is inadequate and continuing importation of new materials from diverse international sources is required. This includes the introduction of further genetic resources of existing species of value, such as perennial ryegrass and white clover, but also species for niche environments, and species of potential value that are new to New Zealand. Regrettably, the application of the current biosecurity and Hazardous Substances and New Organisms rules is not conducive to achieve this outcome, nor positive outcomes related to the use of gene edited plants or microbes. Regulation and its implementation requires urgent attention.

### Future weed and pest challenges

There remain the potential impacts on pasture resilience from so-called 'sleeper weeds and pests,' such as tropical armyworm (*Spodoptera litura*) (Gerard et al. 2011), and the tropical grass webworm (*Herpetogramma licarsisalis*) (Willoughby and Barns 2002) are real. Species such as these are likely to become a significant issue as their range expands with projected climate change. In addition, the effectiveness of *Microctonus* spp. parasitoids against Argentine stem weevil (Ferguson et al. 2019) has diminished through the appearance of resistance (Tomasetto et al. 2017, 2018a, 2018b). Expected changes in climate may result in some existing introduced species becoming problematic weeds, or weed problems spreading to into new regions (Hulme 2012; Cripps et al. 2013; Sheppard et al. 2016; Hulme 2020). Bourdôt et al. (2007) considered that biosecurity efforts to limit the introduction of new plants into New Zealand may be of lesser importance than managing the naturalisation and spread of existing exotic species.

### Soil carbon

Maintaining or increasing soil carbon is considered a crucial component in mitigating impacts of increased carbon dioxide in the atmosphere (Parsons et al. 2009; He Waka Eke Noa 2019; Whitehead 2020; Climate Change Commission 2021; Ministry for the Environment 2021). In New Zealand, conversion from woody vegetation to pasture increased soil carbon by about 13.7 t C/ha to a new steady state (Schipper et al. 2017). Over the subsequent 30 or 40 years there has been a slight decline for some soil types, under some forms of grazing management and under irrigation. Carbon losses from pasture renewal can range between 0.8 and 4.1 t C/ha. A meta-analysis of irrigation effects has shown that irrigation can increase soil carbon levels on most soil types other than coarse textured soils (Emde et al. 2021). While most pasture soils in New Zealand have relatively high levels of carbon sequestration, some have hypothesised that these could be further increased through changed management practices (McNally et al. 2017a; Wall et al. 2021), but other studies acknowledge that most pastoral soils are at equilibrium for soil carbon (Schipper et al. 2014). However, inorganic nutrient availability, including nitrogen (Parsons et al. 2017; Whitehead 2020), is critical for effective and lasting carbon sequestration and as such the availability and value of these nutrients must be recognised (Kirkby et al. 2013). Additionally, the use of 'full inversion tillage' which takes topsoil high in carbon lower into the profile and then allows for further carbon sequestration in the soil brought to the surface (Lawrence-Smith et al. 2021) is being investigated (Hedley et al. 2020).

### *Technology transfer*

The success of technology and knowledge transfer on-farm in New Zealand has been exemplary. This has been due to a combination of peer support and commitment, participatory learning, and partnership between science, consultants, farmers and other agribusiness individuals. This approach has harnessed the drive of farmers in developing and owning the projects (McIvor and Aspin 2001). Nonetheless, the sector is now facing environmental constraints limiting inputs. To manage and mitigate these economically will also require effective communication channels between researchers and farmers.

### *Use of regulated technologies*

The introduction of exotic germplasm has underpinned the success of pastoral agriculture in New Zealand and will remain important for the future. However, under the Hazardous Substances and New Organisms (HSNO) Act and pursuant regulations administered by MAF/MPI as well as the activity of the Environmental Protection Authority (EPA) there have been few instances of new commercially valuable plant material or even their wild relatives being imported since July 1998. This has been identified as a major risk to the future growth of the primary sector (Lancashire 2006). In addition, the HSNO Act regulates the development and testing of genetically modified organisms. The chances of these being used in New Zealand remains low (Ministry for the Environment 2004; Hudson et al. 2019). Movement of this impasse will require new thinking from both the product developers and marketers (Willocks 1999). Two technologies that show potential for reducing methane production in ruminants – the expression of lipids (Winichayakul et al. 2020) and enhanced availability of condensed tannins (Woodfield et al. 2019), are both transgenic and will struggle to find a place in the future of New Zealand pastoral agriculture, despite their potential to mitigate pressing environmental issues. The existence of genetic modification technologies in New Zealand pastoral agriculture while considered an option (Rolleston 2016) remains elusive despite widespread use in medicine. Public debate and reassessment of risks and benefits from these technologies is required. Regulation based on the value and potential risk of the end product/technology is preferable to over-regulating the processes by which such technology is produced, as demonstrated by Canadian regulatory authorities (Smyth 2017; Genome British Columbia 2020).

### *Plant-based and insect-based proteins, and in vitro meats*

Plant-based diets have been heralded as the means to a sustainable global food system resulting in reduced greenhouse gas emissions, improved animal welfare, and enhanced human health (Ferdowsian and Barnard 2009; Faber et al. 2020; Morris and Livesey 2020; United Nations 2020). However, analysis has revealed that alternative protein companies are reporting only their own impact on the environment, not that of the supply chain (Ceres 2021), suggesting that the impact of the plant and energy sources required for product development are ignored.

Willingness to accept a plant-based diet can vary depending on the consumers' cultural origins, their diet preferences, awareness of animal production systems (Wang and Scrimgeour 2021), or in the case of insect-based protein, the fear of the new and unfamiliar (de Koning et al. 2020). It is acknowledged that economics, health/nutrition and aesthetics/taste are important factors in determining consumer food choices rather than explicitly environmental benefit and sustainability (Tucker 2018). A survey of over 1000 consumers from Germany and New Zealand balanced across age, gender and income showed a general preference for meat based rather than *in vitro* meat diets (Lemken et al. 2019). Modelling has indicated that manufacture of cultured meat is not necessarily environmentally superior to cattle (Lynch and Pierrehumbert 2019). Additionally, it is proposed that plant-based diets will incur higher cost to households (Kidd et al. 2021) and on their own may not provide the full nutrition needed for a global population: balanced diet is plant based and animal optimised (Smith et al. 2021). For New Zealand's introduced grassland, the prospect of using grass protein concentrate has shown that refining the extraction method was crucial for achieving optimum protein functionality during its use for food applications (Kaur et al. 2021). *In vitro* meats are being produced using animal cells under laboratory conditions (Post 2012). In New Zealand there is little understanding of this potential food source, and consumers are hesitant to engage with *in vitro* meats due to lack of familiarity (Malavalli et al. 2021). In Europe and USA, many consumers appear willing to eat *in vitro* meats, although in the case of the USA it is deemed unlikely to replace farmed meat in their diet (Hocquette et al. 2015; Wilks and Phillips 2017; Bryant and Dillard 2019). The debate between those promoting alternative protein sources and those supporting the value of conventional livestock production looks set to continue (Sexton et al. 2019).

These latest technological developments could be seen to threaten New Zealand's pastoral sector and indeed, it is possible that market share may decline in some areas, but this will coincide with rapidly growing middle-class populations, particularly in Asia. Based on its *in situ* grassland farming, New Zealand can rightly point to the natural quality of its products and this has appeal compared with vat-based microbial culture production systems. Additionally, it has been estimated that if 10% of the world's meat consumption (i.e. 40 million tonnes) were to be supplied as cultivated meat this would require 4,000 'factories', each with 130 bioreactor lines, and each of these having 10,000 L bioreactor tanks (Food Navigator 2021). It is therefore quite probable that the demand for absolute volumes of premium grass-fed protein will remain or even grow with world protein supplies under threat and demand increasing (McLeod 2011). The importance of protein in reducing malnutrition (Adesogan et al. 2020) ensures that there is a global market sufficient to support both animal and plant-based protein production. The challenge for New Zealand is to ensure that animal protein production is clearly and demonstrably efficient in the use of resources, including land, water, nutrients and energy. This will require new research leading to new technologies providing greater efficiencies of production with reduced and more sustainable inputs. Every effort must be directed to showing that animal-based protein production is not unsustainable, and that consumption of animal protein is a healthy option (Alparslan and Demirbaş 2020).

New Zealand could also become the producer of premium feedstocks that can be used in some of these vat-based foods. Arguably New Zealand's impressive productive base could become more mixed although any transition will be gradual. However, it remains to be seen what the effect of the COVID pandemic will have on patterns of international food production and trade (Aday and Aday 2020; Kaiser et al. 2021).

## Concluding comment

New Zealand's economy is heavily reliant on exports from pastoral agriculture produced from a grassland system based on an introduced ecology. The developments and technologies required to ensure that this introduced ecology can deliver an efficient and effective pastoral production system have been many and varied. Important synergies and discoveries have occurred through effective research and development, a good education system, a professional agribusiness sector and a highly receptive farming community. The latter has been willing to use and adapt technologies that have been the key to its success. However, the outlook is uncertain. The farming community will clearly continue to use new technologies and systems for profitable and sustainable farming systems, but a question remains as to whether the existing research structures and funding systems will be capable of delivering them. Research is difficult, expensive, and uncertain with massive pay-offs to the economy when success occurs.

Priority research topics that will allow New Zealand to rely on pastoral agriculture, which is and will continue to be its competitive advantage, for future economic prosperity:

- Data management systems and extension materials that enable research results to be aggregated and rapidly and effectively communicated to practitioners;
- Farm management systems that allow for the incorporation of biologically sustainable technologies reducing chemical inputs;
- Improvements in animal welfare through appropriate use of shelter;
- Technologies and management systems to continue to further reduce emissions and nutrient losses to the environment;
- Alignment of food production systems with consumer expectations (Eastwood et al. 2019);
- Continued improvement processes to identify and stop potential biosecurity breaches;
- Creation of new added value opportunities from agricultural outputs; e.g. there is emerging new and valuable technologies associated with wool;
- Seek technologies and systems to increase efficient use of resources, including land, water, nutrients and energy;
- Continued improvements in labour productivity through use of time saving technologies;
- Systems for integrating both indigenous and introduced ecosystems;

- Attention to social and ethical aspects of agricultural food production;
- National oversight systems to manage the outcomes for previous (and perhaps current) poor land use management decisions (Bayne and Renwick 2021); and
- The establishment of platforms for very high-quality materials production that support new food technologies such as plant-based proteins.

In short, New Zealand must ensure that structures are in place to promote and allow visionary leadership in the pastoral sector that can inspire and direct solutions to the challenges being faced. These include regulation, consumer demands, and changing market demands, as well as the widely-held beliefs by both urban and rural New Zealanders that the country's farming landscapes and ecology must be protected. Credible science needs to lead the debate on the environmental impacts of grazed pasture to avoid misinformation proliferation. This will require transparent and objective integrity from the science community using funding that requires no defined or preconceived outcomes. To ensure this is achievable, consistent government funding will be imperative, and not simply a nice to have.

## Disclosure statement

John Caradus is employed by Grasslanz Technology Limited and is director of Grasslands Innovation Ltd and Foundation for Arable Research; Jacqueline Rowarth is a director of Ravensdown Ltd, Dairy NZ, Oraka Farming Ltd, Lake Okoroire Ltd, and Two Four Ltd; and Alan Stewart is employed by PGG Wrightson Seeds Ltd.

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## References

Aday S, Aday MS. 2020. Impact of COVID-19 on the food supply chain. Food Qual Safety. 4:167–180.
Addiscott TM. 2005. Nitrate, agriculture and the environment. Wallingford: CABI International, p. 279.
Adesogan AT, Havelaar AH, McKune SL, Eilitta M, Dahl GE. 2020. Animal source foods: sustainability problem or malnutrition and sustainability solution? Perspective matters. Global Food Security. 25. doi:10.1016/j.gfs.2019.100325.
Allan BE, Chapman HM. 1987. Oversown tussock country lessons from 30 years of improvement and management on Tara hills. Proc NZ Grassl Assoc. 48:77–81.
Alparslan OS, Demirbaş N. 2020. Red meat and processed red meat consumption behaviour of healthcare professionals: Do they participate in the World Health Organization's view of red meat carcasses and red meat carcinogens? Public Health Nutrition. 23:214–220. doi:10.1017/S1368980019002453.
Andrews ED. 1955. Cobalt deficiency disease in young sheep. Proc NZ Grassl Assoc. 17:87–95.
Argiriadis E, Battistel D, McWethy DB, Vecchiato M, Kirchgeorg T, Kehrwald NM, Whitlock C, Wilmshurst JM, Barbante C. 2018. Lake sediment fecal and biomass burning biomarkers provide direct evidence for prehistoric human-lit fires in New Zealand. Scientific Reports. 8. doi:10.1038/s41598-018-30606-3.

Arnold R. 1994. New Zealand's burning: The settlers' world in the Mid 1880s. Wellington: Victoria University Press.
Arnst BJ, Park OL. 1984. Pasture establishment on east coast North Island hill country. Proc NZ Grassl Assoc. 45:216–218.
Attwood GT, Wakelin SA, Leahy SC, Rowe S, Clarke S, Chapman DF, Muirhead R, Jacobs JME. 2019. Applications of the soil, plant and rumen microbiomes in pastoral agriculture. Front Nutr. 6: Article 107. doi: 10.3389/fnut.2019.00107.
Australian Bureau of Rural Sciences. 2010. Australia's forests at a glance 2010. Canberra, Australia: Australian Government Department of Agriculture, Fisheries and Forestry.
Baars JA, Cranston A. 1977. The performance of 'Grasslands Matua' prairie grass in the southern North island. Proc NZ Grassl Assoc. 39:148–155.
Ball R. 1969. Legume and fertilizer nitrogen in New Zealand pastoral farming. Proc NZ Grassl Assoc. 31:117–126.
Barker DJ, Sheppard DG, Mackay AD, Dymock N. 1999. Hill country farm investment options – cocksfoot pasture vs. superphosphate fertiliser. Proc NZ Grassl Assoc. Proc. 61:17–21.
Barr S. 1995. A farmer's experience with high N fertiliser inputs on grass/clover pastures. In: Woodfield DR, editor. White clover: NZ's competitive edge. NZ Grassl Assoc Res Pract Ser. No. 6: p. 103–106.
Bascand LD, Jowett GH. 1982. Scrubweed cover of South Island agricultural and pastoral land 2. Plant distribution and managerial problem status. NZ J. Exptal. Agric. 10:455–492.
Basher LR. 2013. Erosion processes and their control in New Zealand. In: Dymond JR, editor. Ecosystem services in New Zealand – conditions and trends. Lincoln, New Zealand: Manaaki Whenua Press; p. 363–374.
Bayne K, Renwick A. 2021. Beyond sustainable intensification: transitioning primary sectors through reconfiguring land-use. Sustainability. 13:3225. doi:10.3390/su13063225.
Beattie J, Star P. 2010. Global influences and local environments: forestry and forest conservation in New Zealand, 1850s-1925. British Scholar. 3:191–218.
Betteridge K, Costall DA, Hutching SM, Devantier BP. 1994. Ragwort (*Senecio jacobaea*) control by sheep in a hill country bull beef system. Proc NZ Plant Prot Conf. 47:53–57.
Bewsell D, Monaghan RM, Kaine G. 2007. Adoption of stream fencing among dairy farmers in four New Zealand catchments. Environ Manage. 40:201–209. doi:10.1007/s00267-006-0184-z.
Blaschke PM, Trustrum NA, DeRose RC. 1992. Ecosystem processes and sustainable land use in New Zealand steeplands. Agric Ecosys Environ. 41:153–178.
Bourdôt GW, Fowler SV, Edwards GR, Kriticos DJ, Kean JM, Rahman A, Parsons AJ. 2007. Pastoral weeds in New Zealand: status and potential solutions. NZ J Agric Res. 50:139–161. doi:10.1080/00288230709510288.
Brazendale R, Bryant JR, Lambert MG, Holmes CW, Fraser TJ. 2011. Pasture persistence: how much is it worth? In: Mercer CF, editor. Pasture Persistence Symposium. NZ Grassl Assoc Res Pract Ser. 15: 3-6.
Brier D, Eastwood C, Rue BD, Viehland D. 2020. Foresighting for responsible innovation using a delphi approach: a case study of virtual fencing innovation in cattle farming. J Agric Environ Ethics. 33:549–569.
Broadfoot KG. 1990. Seed certification. In: Rowarth JS. editor. Management of grass seed crops. NZ Grassl Assoc Res Pract Ser. 5: p. 32–34.
Brock JL, Caradus JR, Hay MJM. 1989. Fifty years of white clover research in New Zealand. Proc NZ Grassl Assoc. 50:25–39.
Brooking T, Pawson E. 2007. Silences of grass: retrieving the role of pasture plants in the development of New Zealand and the British empire. J Imp Commonw Hist. 35:417–435. doi:10.1080/03086530701523406.
Brooking T, Pawson E. 2010. Seeds of empire: the environmental transformation of New Zealand, I.B. Tauris, London. [accessed 2019 May 18]. https://scholar.google.co.nz/scholar?hl=en&as_sdt=0%2C5&q=Brooking%2C+T.%2C+%26+Pawson%2C+E.+%28Eds.%29.+%282011%29.+Seeds+of+empire%3A+The+environmental+transformation+of+New+Zealand.+London%3A+I.+B.+Tauris%2C+296p.+&btnG=.

Brougham RW. 1969. Present position of pasture establishment research in New Zealand. Proc NZ Grassl Assoc. 31:43–51.
Brougham RW. 1981. Pasture management and animal production. Proc NZ Grassl Assoc. 42:54–69.
Brown CD, Green RB. 2003. The challenges facing legumes in a dryland environment - a consultant's view. In: Moot DJ, editor. Legumes for dryland. NZ Grassl Assoc Res Pract Ser. 11: p. 7–12.
Brown WJ. 1991. Landslide control on North Island, New Zealand. Geograph Rev. 81:457–472.
Bryant AM, MacDonald KA, Clayton DG. 1982. Effects of nitrogen fertiliser on production of milk solids from grazed pasture. Proc NZ Grassl Assoc. 43:58–63.
Bryant CJ, Dillard C. 2019. The impact of framing on acceptance of cultured meat. Front Nutr. 6:103.
Buxton DAL. 1981. Economics of nitrogen use in dairying. Proc NZ Grassl Assoc. 43:70–75.
Cameron D. 2016. Sustaining the productivity of New Zealand's hill country – A land manager's view. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 151-155.
Campbell-Hunt D. 1997. Scenarios and strategic thinking. Proc. Primary Industry Conf. Wellington. 122–126.
Caradus JR. 2006. 75 years of scientific and technological advances in pastoral agriculture – what will it take to continue to deliver? Proc NZ Grassl Assoc. 68:33–68.
Caradus JR. 2007. Pastoral agriculture – New Zealand's competitive advantage. Proc NZ Grassl Assoc. 69:1–10.
Caradus JR, Card SD, Finch SC, Hume DE, Johnson LJ, Mace WJ, Popay AJ. 2020. Ergot alkaloids in New Zealand pastures and their impact. NZ J. Agric. Res. doi:10.1080/00288233.2020.1785514.
Caradus JR, Chapman DF, Cookson T, Cotching B, Deighton MH, Donnelly L, Ferguson J, Finch SC, Gard S, Hume DE, et al. 2021. *Epichloë* endophytes – new perspectives on a key ingredient for resilient perennial grass pastures. In: Douglas G, editor. Resilient Pasture Symposium. NZ Grassl Assoc Res Pract Ser. 17: doi.org/10.33584/rps.17.2021.3435.
Caradus JR, Clark DA. 2001. Advancing dairy farming profitability through research. Proc NZ Grassl Assoc. 63:17–22.
Caradus JR, Hay RJM, Woodfield DR. 1995a. The positioning of white clover cultivars in New Zealand. In: Woodfield DR, editor. White clover: NZ's competitive edge. NZ Grassl Assoc Res Pract Ser. 6: p. 45–49.
Caradus JR, Johnson LJ. 2019. Improved adaptation of temperate grasses through mutualism with fungal endophytes. In: Schouten A, editor. Endophyte biotechnology: promise for agriculture and pharmacology. CAB International; p. 85–108.
Caradus JR, Lovatt S, Belgrave B. 2013. Adoption of forage technologies. Proc NZ Grassl Assoc. 75:39–44.
Caradus JR, Woodfield DR, Stewart AV. 1995b. Overview and vision for white clover. In: Woodfield DR, editor. White clover: New Zealand's competitive edge. NZ Grassl Assoc Res Pract Ser. 6: p. 1-6.
Carran RA. 1978. Soil nitrogen and pasture management. Proc NZ Grassl Assoc. 40:44–50.
Ceres. 2021. Climate Action 100+ Net-Zero Company Benchmark. [accessed 2021 November 6] https://www.ceres.org/resources/tools/climate-action-100-net-zero-company-benchmark.
Chapman DF, Bryant JR, Olayemi ME, Edwards GR, Thorrold BS, McMillan WH, Kerr GA, Judson G, Cookson T, Moorhead A, Norriss M. 2017. An economically based evaluation index for perennial and short-term ryegrasses in New Zealand dairy farm systems. Grass Forage Sci. 72:1–21.
Chapman DF, Campbell BD, Harris PS. 1985. Establishment of ryegrass, cocksfoot, and white clover by oversowing in hill country. NZ J Agric Res. 28:177–189. doi:10.1080/00288233.1985.10420927.
Charlton JFL. 1991. Some basic concepts of pasture seed mixtures for New Zealand farms. Proc NZ Grassl Assoc. 53:37–40.

Charlton JFL, Belgrave BR. 1992. The range of pasture species in New Zealand and their use in different environments. Proc NZ Grassl Assoc. 54:99–104.
Charlton JFL, Stewart AV. 1999. Pasture species and cultivars used in New Zealand – a list. Proc NZ Grassl Assoc. 61:147–166.
Charlton JFL, Stewart AV. 2000. Timothy - the plant and its use on New Zealand farms. Proc NZ Grassl Assoc. 62:147–153.
Chestnut K. 1986. Pasture renovation for increased dairy production. Proc NZ Grassl Assoc. 47:155–157.
Chok SE, Grafton MCE, Yule IJ, Manning MJ. 2016. Capability of ground fertiliser placement when spread from fixed wing aircraft. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 191-196.
Clark AH. 1949. The invasion of New Zealand by people, plants and animals. New Brunswick: Rutgers University Press, p. xiv + 465.
Clark H, Kelliher F, Pinares-Patino C. 2011. Reducing CH4 emissions from grazing ruminants in New Zealand: challenges and opportunities. Asian-Aust J Anim Sci. 24:295–302.
Climate Change Commission. 2021. Ināia tonu nei: a low emissions future for Aotearoa. Pp 1-148. https://ccc-production-media.s3.ap-southeast-2.amazonaws.com/public/Inaia-tonu-nei-a-low-emissions-future-for-Aotearoa/Inaia-tonu-nei-a-low-emissions-future-for-Aotearoa.pdf [accessed 2021 July 12].
Close ME, Humphries B, Northcott G. 2021. Outcomes of the first combined national survey of pesticides and emerging organic contaminants (EOCs) in groundwater in New Zealand 2018. Sci. Total Environ. 754. doi:10.1016/j.scitotenv.2020.142005
Cochrane GR. 1976. Remote sensing applications in pasture analysis. Proc NZ Grassl Assoc. 38:226–245.
Cockayne AH. 1913. Seed-testing. The determination of purity. J Agric. 6:481–488.
Cocks A, Williams M, Casey M, Brown C, Ware J, Morrison N, Morrison G, Pearce G, Taylor W, Cochrane G, et al. 2002. Farmers adopting technology to improve sheep production – a nine year study. Proc NZ Grassl Assoc. 64:49–53.
Coles GD, Wratten SD, Porter JR. 2016. Food and nutritional security requires adequate protein as well as energy, delivered from whole-year crop production. PeerJ. 4:e2100. doi:10.7717/peerj.2100. [accessed 2021 August 23].
Connell RP. 1933. Some aspects of problems relative to increased application of knowledge of grass farming. Proc NZ Grassl Assoc. 2:5. https://www.grassland.org.nz/publications/nzgrassland_publication_2159.pdf.
Corkill L, Williams WM, Lancashire J. 1981. Pasture species and cultivars for regions. Proc NZ Grassl Assoc. 12: 100–122.
Cosgrove GP. 2005. Novel grazing management: making better use of white clover. Proc South Island Dairy Event, June 2005. Pp 181-189.
Cressey P, Cridge B. 2021. Nitrate in food and water. July 2021 Prepared for NZ Food Safety Science Research Centre, ESR Report Number: CSC21025.
Cripps M, Bourdôt G, Fowler S. 2013. Sleeper thistles in New Zealand status and biocontrol potential. Proc. NZ Plant Protection. 66:99–104.
Crofoot A. 2016. Impact of Government and regulatory policy on hill country farming. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 29-32.
Crump DK. 1985. Seed certification - an aspect of quality assurance with special reference to white clover seed. In: Hare MD, Brock JL, editor. Producing herbage seeds. NZ Grassl Assoc Res Pract Ser. 2: p. 75–78.
Crush JR. 1973. The effect of *Rhizophagus tenuis* mycorrhizas on ryegrass, cocksfoot and sweet vernal. New Phytol. 72:965–973.
Crush JR. 1978. Changes in effectiveness of soil endomycorrhizal fungal populations during pasture development. NZ J Agric Res. 21(4):683–685. doi:10.1080/00288233.1978.10427466.
Crush JR, Caradus JR. 1980. Effect of mycorrhizas on growth of some white clovers. NZ J Agric Res. 23:233–237.

Cumberland K. 1981. Landmarks: how New Zealanders remade their landscape. Readers Dig. Serv. Pty Limited, Surry Hills, New South Wales. [accessed 2019 May 18]. https://scholar.google.co.nz/scholar?cluster=16953464723247731141&hl=en&as_sdt=2005&sciodt=0,5.
Cumberland KB. 1941. A century's change: natural to cultural vegetation in New Zealand. Geographical Rev. 31:529–554.
Cumberland KB. 1947. Soil erosion in New Zealand. 2nd ed. Wellington: Whitcombe & Tombs, p.228.
Cunningham IJ. 1944. Copper deficiency in cattle and sheep. Occurrence and control in N.Z. NZ J Agric Res. 89:559–569.
Curtin D, Peterson ME, Qiu W, Fraser P. 2020. Predicting soil pH changes in response to application of urea and sheep urine. J. Environ. Qual. 49:1445–1452.
Curtis PG, Slay CM, Harris NL, Tyukavina A, Hansen MC. 2018. Classifying drivers of global forest loss. Science. 361:1108–1111. https://science.sciencemag.org/content/sci/361/6407/1108.full.pdf.
Daigneault AJ, Eppink FV, Lee WG. 2017. A national riparian restoration programme in New Zealand: is it value for money? J Environ Manage. 187:166–177.
DairyNZ. 2021a. Economic Survey 2019 -20. Hamilton, New Zealand. Pp. 78. [accessed 2021 August 24] https://www.dairynz.co.nz/media/5794600/dairynz-economic-survey-2019-20.pdf.
DairyNZ. 2021b. Pasture growth forecaster. [accessed 2021 August 28] http://pasture-growth-forecaster.dairynz.co.nz/.
Daly MJ, Fraser T, Perkins A, Moffat CM. 1999. Farmer perceptions of reasons for perennial pasture persistence and the relationship of these with management practice, species composition, and soil fertility. Proc NZ Grassl Assoc. 61:9–15.
Davies EB. 1952. Molybdenum research in New Zealand. Proc NZ Grassl Assoc. 14:182–191.
Dawson M. 2016. New Zealand's native brooms: overlooked treasures? NZ Garden J. 19:6–13.
de Koning W, Dean D D, Vriesekoop F, Aguiar LK, Anderson M, Mongondry P, Oppong-Gyamfi K, Urbano B, Luciano CAG, Jiang B, et al. 2020. Drivers and inhibitors in the acceptance of meat alternatives: the case of plant and insect-based proteins. Foods. 9:1292. doi:10.3390/foods9091292.
Delaby L, Finn JA, Grange G, Horan B. 2020. Pasture-based dairy systems in temperate lowlands: challenges and opportunities for the future. Front Sustain Food Syst. 4:543587. doi: 10.3389/fsufs.2020.543587.
Di HJ, Cameron KC. 2002. The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland. Soil Use Management. 18:395–403.
Dignam BEA, O'Callaghan M, Condron LM, Kowalchuk GA, Van Nostrand JD, Zhou J, Wakelin SA. 2018. Effect of land use and soil organic matter quality on the structure and function of microbial communities in pastoral soils: Implications for disease suppression. PLoS ONE. 13: e0196581. doi:10.1371/journal.pone.0196581.
Dignam BEA, O'Callaghan M, Condron LM, Raaijmakers JM, Kowalchuk GA, Wakelin SA. 2019. Impacts of long-term plant residue management on soil organic matter quality, *Pseudomonas* community structure and disease suppressiveness. Soil Biol Biochem. 135:396–406.
Dodd M, Barker G, Burns B, Didham R, Innes J, King C, Smale M, Watts C. 2011. Resilience of New Zealand indigenous forest fragments to impacts of livestock and pest mammals. NZ J Ecol. *35*:83–95.
Douglas GB, Mcivor IR, Manderson AK, Koolaard JO, Todd M, Braaksma S, Gray RAJ. 2013. Reducing shallow landslide occurrence in pastoral hill country using wide-spaced trees. Land Degrad. Dev. 24:103–114. doi:10.1002/ldr.1106.
Duin EC, Wagner T, Shima S, Prakash D, Cronin B, Yáñez-Ruiz S, Duval S, Rümbeli R, Stemmler RT, Thauer RK. 2016. Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. Proc. Nat Acad Sci. 113:6172–6177.

Easton HS, Baird D, Baxter G, Cameron N, Hainsworth R, Johnston C, Kerr G, Lyons T, McCabe R, Nichol W, et al. 1997. Annual and hybrid ryegrass cultivars in New Zealand. Proc NZ Grassl Assoc. 59:239–244.
Eastwood C, Klerkx L, Ayre M, Dela Rue B. 2019. Managing socio-ethical challenges in the development of smart farming: from a fragmented to a comprehensive approach for responsible research and innovation. J Agric Environ Ethics. 32:741–768.
Edmeades DC, McBride RM, Gray M. 2016. An assessment of current fertiliser practices in New Zealand hill country. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 173-178.
Edmeades DC, O'Connor MB. 2003. Sodium requirements for temperate pastures in New Zealand: a review. NZ J Agric Res. 46:37–47.
Emde D, Hannam K, Most I, Nelson L, Jones M. 2021. Soil organic carbon in irrigated agricultural systems: a meta-analysis. Global Change Biology. 13. doi:10.1111/gcb.15680
Espie PR. 1994. Integrated pastoral management strategies for *Hieracium* control. Proc NZ Grassl Assoc. 56:243–247.
Evans RN. 2004. Introduction to farming in the central Canterbury area. Proc NZ Grassl Assoc. 66:5–10.
Ewers RM, Kliskey AD, Walker S, Rutledge D, Harding JS, Didham RK. 2006. Past and future trajectories of forest loss in New Zealand. Biol Conservation. 133:312–325.
Faber I, Castellanos-Feijoo NA, Van de Sompel L, Davydova A, PerezCueto FJA. 2020. Attitudes and knowledge towards plant-based diets of young adults across four European countries. exploratory survey. Appetite. 145. doi:10.1016/j.appet.2019.104498.
Farmax. http://www.farmax.co.nz/ [accessed 2021 August 28].
Fasi V, Mills A, Moot DJ, Scott WR, Pollock KM. 2008. Establishment, annual yield and nitrogen response of eight perennial grasses in a high country environment. Proc NZ Grassl Assoc. 70:123–130.
Fennessey PF, Glennie SF, McCorkindale AB. 2016. Innovations behind the farm gate that will influence performance of hill farming. In: Thom ER, editor. "Hill Country Symposium". NZ Grassl Assoc Res Pract Ser. 16: 15-20.
Ferdowsian HR, Barnard ND. 2009. Effects of plant-based diets on plasma lipids. Amer J Cardiol. 104:947–956. doi:10.1016/j.amjcard.2009.05.032.
Ferguson CM, Barratt BIP, Bell B, Goldson SL, Hardwick S, Jackson M, Jackson TA, Phillips CB, Popay AJ, Rennie G, et al. 2019. Quantifying the economic cost of invertebrate pests to New Zealand's pastoral industry. NZ J Agric Res. 62:255–315.
Fernández-Arhex V, Corley JC. 2003. The functional response of parasitoids and its implications for biological control. Biocontrol Sci Technol. 13:403–413. doi: 10.1080/0958315031000104523.
Food Navigator. 2021. Cell-based disruption: how many factories, and at what capacity, are required to supply 10% of the meat market? [accessed 2021 August 28] https://www.foodnavigator.com/Article/2021/08/13/Cell-based-disruption-How-many-factories-and-at-what-capacity-are-required-to-supply-10-of-the-meat-market?utm_source=newsletter_daily&utm_medium=email&utm_campaign=13-Aug-2021&cid=DM975676&bid=1678664138.
Fowler SV, Paynter Q, Hayes L, Dodd S, Groenteman R. 2010. Biocontrol of weeds in New Zealand: an overview of nearly 85 years. In: Seventeenth Australasian Weeds Conference. Christchurch, New Zealand, New Zealand Plant Protection Society, pp. 211-214.
Fraser TJ, Stevens DR, Schofield RW, Nelson BJ, Nelson AJ, Shortland SM. 2016. Improved forages to enhance hill country sheep production. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 225-231.
Genome British Columbia. 2020. Regulation of genetically modified and genetically engineered products in Canada. [accessed 2021 November 7]. https://www.genomebc.ca/infobulletins/regulation-of-genetically-modified-and-genetically-engineered-products-in-canada.
Gerard PJ, Addison PJ, Hedley P, Bell NL, Vink CJ. 2011. Outbreak of armyworms in eastern Bay of plenty. Proc NZ Plant Prot. 64:285. (Abstract). https://www.journal.nzpps.org/index.php/nzpp/article/view/5989.

Ghanizadeh H, Harrington KC. 2019. Weed management in New Zealand pastures. Agron. 9:448. doi:10.3390/agronomy9080448.
Gibbs HS. 1963. Soils of New Zealand and their limitations for pastoral use. NZ Soil Bureau Publication No. 308. Pp. 16.
Giller KE, Hijbeek R, Andersson JA, Sumberg J. 2021. Regenerative agriculture: an agronomic perspective. Outlook on Agriculture. 50:13–25. doi:10.1177/0030727021998063.
Gillespie BJ, Lucas RJ, Moot DJ, Edwards GR. 2006. Can topdressing with salt increase oversowing success and pasture quality on steep, south facing slopes in hill country pastures? Proc NZ Grassl Assoc. 68:349–353.
Gillingham AG, Gray MH, Morton JD. 2004. Animal production, economic results and lessons from nitrogen fertiliser use on dry hill country. Proc NZ Grassl Assoc. 66:35–40.
Gillingham AG, Maber J, Morton J, Tuohy M. 1999. Precise aerial fertiliser application on hill country. Proc NZ Grassl Assoc. 61:221–226.
Gillingham AG, Ricardson SC, Riley J. 1984. Rationalising topdressing of hill country. Proc NZ Grassl Assoc. 45:92–97.
Glassey CB, Roach CG, Lee JM, Clark DA. 2013. The impact of farming without nitrogen fertiliser for ten years on pasture yield and composition, milksolids production and profitability; a research farmlet comparison. Proc NZ Grassl Assoc. 75:71–78.
Glassey CB, Roach CG, Strahan MR, McClean N. 2010. Dry matter yield, pasture quality and profit on two Waikato dairy farms after pasture renewal. Proc NZ Grassl Assoc. 72:91–96.
Golding KP, Wilson ED, Kemp PD, Pain SJ, Kenyon PR, Morris ST, Hutton PG. 2011. Mixed herb and legume pasture improves the growth of lambs post-weaning. Animal Prod Sci. 51:717–723.
Goldson SL, Barker GM, Chapman HM, Popay AJ, Stewart AV, Caradus JR, et al. 2020. Severe insect pest impacts on New Zealand pasture: the plight of an ecological outlier. J. Insect Sci. 20:1–17. doi:10.1093/jisesa/ieaa018.
Goldson SL, Rowarth JS, Caradus JR. 2005. The impact of invasive invertebrate pests in pastoral agriculture: a review. NZ J Agric Res. 48:401–415.
Goldson SL, Tomasetto F, Jacobs JME, Barratt BIP, Wratten SD, Emberson RM, Tylianakis J. 2017. Rapid biocontrol evolution in New Zealand's species-sparse pastureland. In: Mason PG, Gillespie DR, Vincent C. editors. Proceedings of the 5th International Symposium on Biological Control of Arthropods. Langkawi, Malaysia, September 11-15. Pp. 32-34.
Gorman LW. 1934. Some observations on strain in clovers. Proc NZ Grassl Assoc. 3:5.
Grace ND. 1969. Trace element problem in the Wairarapa. Proc NZ Grassl Assoc. 31:65–70.
Grace ND. 1992. Prevention of trace element deficiencies in grazing ruminants: an evaluation of methods. Proc NZ Grassl Assoc. 54:31–34.
Grace ND. 1994. Managing trace element deficiencies. Occasional publication. New Zealand Pastoral Agricultural Research Institute Ltd. 9–24.
Grace ND, Clark RG. 1991. Trace element requirements, diagnosis and prevention of deficiencies in sheep and cattle. In: Tsuda T, Sasaki Y, Kawashima R, editors. Physiological aspects of digestion and metabolism in ruminants. Academic Press, p. 321–346. doi:10.1016/B978-0-12-702290-1.50022-9.
Grace ND, Knowles SO, West DM. 2011. Dose-response effects of long-acting injectable vitamin B12 plus selenium (Se) on the vitamin B12 and Se status of ewes and their lambs. NZ Vet. J. 54:67–72.
Grace ND, West DM. 2006. Effect of Se-amended fertilisers on the Se status of grazing dairy cattle. Proc. NZ Soc. Animal Prod. 66:182–186.
Grant DA, Brock JL. 1974. A survey of pasture composition in relation to soils and topography on a hill country farm in the southern Ruahine range. New Zealand. NZ J Exptal Agric. 2:243–250. doi:10.1080/03015521.1974.10427683.
Gray DIS, Hartnell MAM, Wood BA, Kemp PD, Blair HT, Kenyon PR, Morris ST. 2016. Improved extension practices for sheep and beef farmers. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 61-66.
Gregg P. 2008. Soil erosion and conservation. Te Ara - the encyclopedia of New Zealand. [accessed 2021 June 13]. http://www.TeAra.govt.nz/en/soil-erosion-and-conservation/print.

Guthrie-Smith H. 1969. Tutira - The story of a New Zealand sheep station, 4th ed. Wellington: A.H. & A.W. Reed.
Haggerty J, Campbell H. 2008. 'Farming and the environment', Te Ara - the Encyclopedia of New Zealand. http://www.TeAra.govt.nz/en/farming-and-the-environment [accessed 2021 March 6].
Hall IR. 1987. Introduction of grasses into tussockgrasslands. Proc NZ Grassl Assoc. 48:171–175.
Harris SL, Auldist MJ, Clark DA, Jansen EBL. 1998. Effects of white clover content in the diet on herbage intake, milk production and milk composition of New Zealand dairy cows housed indoors. J Dairy Res. 65:389–400.
Harris SL, Clark DA. 1996. Effect of high nitrogen fertiliser rates on white clover growth, morphology and nitrogen fixation activity in grazed dairy pasture in northern New Zealand. NZ J Agric Res. 39:149–158.
Harris SL, Clark DA, Auldist MJ, Waugh CD, Laboyrie PG. 1997. Optimum white clover content for dairy pastures. Proc NZ Grassl Assoc. 59:29–33.
Harris SL, Penno JW, Bryant AM. 1994. Effects of high rates of nitrogen fertiliser on dairy pastures and production. Proc NZ Grassl Assoc. 56:27–31.
Hartley MJ, Atkinson GC, Bimler KH, James TK, Popay I. 1978. Control of barley grass by grazing management. Proc NZ Weed Pest Control Conf. 31:198–202.
Hartley MJ, Thai PH. 1979. Effect of pasture species and grazing on survival of seedling gorse. Proc NZ Weed Pest Control Conf. 32:297–302.
Hawes P, Memom PA. 1998. Prospects for sustainable management of indigenous forests on private land in New Zealand. J Environ Manage. 52:113–130.
Hawke MF, O'Connor MB, Johnston TJM, Waller JE, Addison B. 1994. Monitoring cobalt status - experiences in the central North island. Proc NZ Grassl Assoc. 56:249–254.
Hawkins BA, Cornell HV. 2008. Theoretical approaches to biological control. Cambridge: Cambridge University Press. ISBN 9781139429283. https://books.google.co.nz/books?id=HSRBcKtrsAEC.
Healy A. 1952. The introduction and spread of weeds. Proc. NZ Weed Control Conf. 5:5–16.
Hedley CB, Yule IJ, Tuohy M, Vogeler I. 2009. Key performance indicators for simulated variable-rate irrigation of variable soils in humid regions. Trans Amer Soc Agric Biol Eng. 52:1575–1584. doi:10.13031/2013.29146.
Hedley MJ, Beare MH, Calvelo PR, McNally SR, Smith LEJ, Tregurtha CS, Osborne MA, Gillespie RN, Van der Klei G, Thomas SM. 2020. Where, when and how - practise guidelines for successful introduction of full inversion tillage to increase soil carbon stocks under pasture. In: Christensen L, Horne DJ, Singh R, editor. Nutrient management in farmed landscapes. Occasional Report No. 33. Farmed landscapes research centre. Palmerston North, New Zealand: Massey University; p. 9; http://flrc.massey.ac.nz/publications.html.
Heiler T. 2008. Irrigation and drainage - beginnings of irrigation, Te Ara - the Encyclopedia of New Zealand. [accessed 2021 November 6]. http://www.TeAra.govt.nz/en/irrigation-and-drainage/page-2.
He Waka Eke Noa. 2019. He Waka Eke Noa—our future in our hands - primary sector climate change commitment. https://hewakaekenoa.nz/wp-content/uploads/2020/12/primary-sector-climate-change-commitment-july-2019.pdf [accessed 2021 August 21].
Hicks DM, Shankar U, McKerchar AI, Basher L, Lynn I, Page M, Jessen M. 2011. Suspended sediment yields from New Zealand rivers. J Hydrol. (NZ). 50:81–142.
Hight GK. 1979. Hill country: A major agricultural resource and its capacity for increased production. Proc NZ Soc Anim Prod. 39:1–12.
Hocquette A, Lambert C, Sinquin C, Peterolff L, Wagner Z, Bonny SP, Lebert A, Hocquette J-F. 2015. Educated consumers don't believe artificial meat is the solution to the problems with the meat industry. J Integr Agric. 14:273–284.
Hoglund JH, White JGH. 1985. Environmental and agronomic constraints in dryland pasture and choice of species. In: Burgess RE, Brock JL, editors. Using herbage cultivars. NZ Grassl Assoc Res Pract Ser. 3: p. 39–43.
Holden JS. 1965. The economics of hill country development. Proc NZ Grassl Assoc. 27:64–74.

Holford GH. 1933. Grassland work overseas. Proceeding of the New Zealand Grassland Association. 2:4. https://www.grassland.org.nz/publications/nzgrassland_publication_2169.pdf.

Holmes CW. 1982. The effect of fertiliser nitrogen on the production of pasture and milk on dairy farmlets: 1971-1974. Proc NZ Grassl Assoc. 43:53–57.

Hoogendoorn CJ, Betteridge K, Costall DA, Ledgard SF. 2010. Nitrogen concentration in the urine of cattle, sheep and deer grazing a common ryegrass/cocksfoot/ white clover pasture. NZ J Agric Res. 53:235–243. doi:10.1080/00288233.2010.499899.

Horan B, Roche JR. 2020. Defining resilience in pasture-based dairy-farm systems in temperate regions. Animal Prod Sci. 60:55–66. doi:10.1071/AN18601.

Hudson M, Mead ATP, Chagné D, Roskruge N, Morrison S, Wilcox PL, Allan AC. 2019. Indigenous perspectives and gene editing in Aotearoa New Zealand. Front Bioengin Biotech. 7:1–9.

Hulme PE. 2012. Weed risk assessment: a way forward or a waste of time? Journal of Appl. Ecol. 49:10–19.

Hulme PE. 2020. Plant invasions in New Zealand: global lessons in prevention, eradication and control. Biol Invasions. 22:1539–1562.

ICAP. 2021. Emissions trading systems and Net Zero: Trading Removals. [accessed 2021 August 28] https://icapcarbonaction.com/en/?option=com_attach&task=download&id=743.

Innes J, Fitzgerald N, Binny R, Byrom A, Pech R, Watts C, Gillies C, Maitland M, Campbell-Hunt C, Burns B. 2019. New Zealand ecosanctuaries: types, attributes and outcomes. J. Royal Soc. NZ. 49:370–393. doi:10.1080/03036758.2019.1620297.

James OG. 1984. Agricultural aviation at the cross roads. Proc NZ Grassl Assoc. 45:9–14.

Jensen H, Orth B, Reiser R, Bürge D, Lehto NJ, Almond P, Gaw S, Thomson B, Lilburne L, Robinson B. 2019. Environmental parameters affecting the concentration of iodine in New Zealand pasture. J. Environ. Qual. 48:1517–1523.

Jones H, Clough P, Hock B, Phillips C. 2008. Economic costs of hill country erosion and benefits of mitigation in New Zealand: Review and recommendation of approach. Ministry of Agriculture and Forestry Contract No: 74701. [accessed 2021 July 18] https://d1wqtxts1xzle7.cloudfront.net/48500699/Economic_costs_of_hill_country_erosion_a20160901-17645-1ct4wlc.pdf?1472781242=&response-content-disposition=inline%3B+filename%3DEconomic_costs_of_hill_country_erosion_a.pdf&Expires=1626582960&Signature=FVQriOjhaxa1uSfxBIFFA84IosLAilEWJbhg7oVVo-fUjh3zT0mC8G0UvLNmvElsx4lODQ~jr8OWyAv-SRgQIADfg2ZV5TedpHlESj~69sBm2poR-4t4nR7BtlIuw2U9g4wFdaq~am77q9aCExoISTn47wOv0Qzojzs2mJjJRv2dmVvKYw8QFGpzGp1EUXFksAFB-L5ODbucKmdtwL5WUvFdhBl1F1k~akTlN6qbrR~wC0OQlO6AwXHwMpBjptG4CPvx5-Om4YcuDIo58e1c-min7M92Ar5J8gdAKnfLyb~WD~dsdLUOf3bmOghoDnA270Hfl2Y9DBuaNziv2e5oUw__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA.

Jones V. 1988. 50 years of power fencing. Proc NZ Grassl Assoc. 49:145–149.

Journeaux P, Manning M, Roberts AHC. 2013. Economics of fertiliser application on hill country. In: Currie LD, Christensen CL, editor. Accurate and efficient use of nutrients on farms Occasional Report No. 26. Fertilizer and lime research centre. Palmerston North, New Zealand: Massey University; p. 12; http://flrc.massey.ac.nz/publications.html.

Julian JP, de Beurs KM, Owsley B, Davies-Colley RJ, Ausseil AGE. 2017. River water quality changes in New Zealand over 26 years: response to land use intensity. Hydrol Earth Syst. Sci. 21:1149–1171.

Kaiser M, Goldson S, Buklijas T, Gluckman P, Allen K, Bardsley A, Lam ME. 2021. Towards post-pandemic sustainable and ethical food systems. Food Ethics. 6:1–19. doi:10.1007/s41055-020-00084-3.

Kalusová V, Chytrý M, van Kleunen M, Mucina L, Dawson W, Essl F, Kreft H, Pergl J, Weigelt P, Winter M, Pyšek P. 2017. Naturalization of European plants on other continents: the role of donor habitats. Proc Natl Acad Sci. USA. 114:13756–13761. doi:10.1073/pnas.1705487114.

Kaur L, Lamsar H, López IF, Filippi M, Ong Shu Min D, Ah-Sing K, Singh J. 2021. Physico-chemical characteristics and in vitro gastro-small intestinal digestion of New Zealand ryegrass proteins. Foods 10: Article 331. doi:10.3390/foods 10020331

Kelly S, Smith E, Brazendale R. 2011. Pasture renewal in the Waikato and Bay of Plenty regions: An overview of farmer practice, experience and attitudes. In: Mercer CF, editor. Pasture Persistence Symposium. NZ Grassl Assoc Res Pract Ser. 15: 21-24.
Kemp PD, Lopez IF. 2016. Hill country pastures in the southern North Island of New Zealand: an overview. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 289-298.
Kerr GA. 2020. NZGA president's address 2019: smarter pasture renewal plus objective thinking. J NZ Grassl. 82:7–10.
Kidd B, Mackay S, Vandevijvere S, Swinburn B. 2021. Cost and greenhouse gas emissions of current, healthy, flexitarian and vegan diets in Aotearoa (New Zealand). BMJ Nutrition, Prevention & Health 2021. doi:10.1136/ bmjnph-2021-000262
King CM. 1984. Immigrant killers: introduced predators and the conservation of birds in New Zealand. Auckland: Oxford University Press.
King M. 1969. The influence of soil conservation on hill country management. Proc NZ Grassl Assoc. 31:80–86.
King W, Rennie GM, Devantier B, Hoogendoorn CJ. 2016. Impacts of grazing management on hill country pastures: principles and practices. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16:203-212.
Kirkby CA, Richardson AE, Wade LJ, Batten GD, Blanchard C, Kirkegaard JA. 2013. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol Biochem. 60:77–86.
Knight C. 2009. The paradox of discourse concerning deforestation in New Zealand: a historical survey. Environ Hist. 15:3232–3342.
Kuntz M. 2020. Glyphosate, separating "the wheat from the tares". The Fondation pour l'innovation politique. Pp. 63. https://www.scribd.com/document/488922412/Fondapol-Study-Glyphosate-Marcel-Kuntz-12-2020.
Lambert MG. 1976. The influence of aspect on pasture environment. Proc NZ Grassl Assoc. 38:78–86.
Lambert MG, Clark DA. 1986. Effects of late-autumn nitrogen application on hill country pastures and sheep production. Proc NZ Grassl Assoc. 47:211–215.
Lambert MG, Litherland AJ. 2000. A practitioner's guide to pasture quality. Proc NZ Grassl Assoc. 62:111–115.
Lambert MG, Paine MS, Sheath GW, Webby RW, Litherland AJ, Fraser TJ, Stevens DR. 2000. How do sheep and beef farmers manage pasture quality? Proc NZ Grassl Assoc. 62:117–121.
Lancashire JA. 1990. Special address: 150 years of grassland development in New Zealand. Proc NZ Grassl Assoc. 52:9–15.
Lancashire JA. 2006. The value of exotic germplasm to the NZ livestock industry. In: Mercer CF, editor. Breeding for Success: Diversity in Action. Proc. 13th Australasian Plant Breeding Conf., Christchurch, New Zealand 18-21 April 2006. pp. 1034-1041.
Lane GA. 1999. Chemistry of endophytes: patterns and diversity. In: Woodfield DR, Matthew C, editors. Ryegrass endophyte: an essential New Zealand symbiosis. NZ Grassl Assoc Res Pract Ser. 7: p. 85–94.
Langer RHM. 1977. Pastures and pasture plants. In Langer RHM, editor. Wellington: AH and AW reed, p. 430.
Langer RHM. 1990. Pastures: their ecology and management (No. 04; SB199, L3.). Auckland, New Zealand: Oxford University Press. [accessed 2018 August 3] http://agris.fao.org/agris-search/search.do?recordID=US201300674236
Laurenson S, van der Weerden TJ, Beukes PC, Vogeler I. 2017. Evaluating the economic and production benefit of removing dairy cows from pastures in response to wet soil conditions. NZ J Agric Res. 60:223–244. doi:10.1080/00288233.2017.1298630.
Lawrence-Smith EJ, Curtin D, Beare MH, McNally SR, Kelliher FM, Pereira RC, Hedley MJ. 2021. Full inversion tillage during pasture renewal to increase soil carbon storage: New Zealand as a case study. Glob Chang Biol. 271:998–2010.
Ledgard SF. 2017. Assessing the environmental impact of sheep production. In: J. Greyling, editor. Achieving sustainable production of sheep. Burleigh Dodds series in agricultural science book 22. Cambridge (UK). p. 407–430. doi:10.19103/ AS.2016.0019.20

Lee KE. 1961. Interactions between native and introduced earthworms. Proc NZ Ecol Soc. 8:60–62.
Lemken D, Spiller A, Schulze-Ehlers B. 2019. More room for legume – consumer acceptance of meat substitution with classic, processed and meat-resembling legume products. Appetite 143. doi:10.1016/j.appet.2019.104412
Le Prou R. 2007. The administration of New Zealand irrigation: history and analysis. Report from New Zealand Institute for the Study of Competition and Regulation, Victoria University of Wellington, Pp. 37. [accessed 2021 July 17]. http://hdl.handle.net/10063/3954.
Levy EB. 1970. Grasslands of New Zealand. 3rd ed. Lincoln University, p. 374. AgYields National Database. [accessed 2021 August 28] https://www.agyields.co.nz/home
Lissaman WJ, Casey M, Rowarth JS. 2013. Innovation and technology uptake on farm. Proc NZ Grassl Assoc. 75:27–32.
Lobb WR. 1968. Irrigation. Proc NZ Grassl Assoc. 30:21–30.
Longhurst RD, Luo J, O'Connor MB, Pow T. 2006a. Herd homes: nutrient management and farmer perceptions of performance. Proc NZ Grassl Assoc. 68:309–313.
Longhurst RD, Miller D, Williams I, Lambourne A. 2006b. On-farm wintering systems – issues to consider. Proc NZ Grassl Assoc. 68:289–292.
Luscombe 1979. Nitrogen fertiliser responses on hill country pastures. Proc NZ Grassl Assoc. 41: 155–162.
Luscombe PC, Fletcher RH. 1982. Nitrogen fertiliser on grazed hill pastures. Proc NZ Grassl Assoc. 43:171–180.
Lynch J, Pierrehumbert R. 2019. Climate impacts of cultured meat and beef cattle. Frontiers in Sustainable Food Systems 3: Article 5. doi: 10.3389/fsufs.2019.00005
MacDonald KA, Matthew C, Glassey CB, McLean N. 2011. Dairy farm systems to aid persistence. In: Mercer CF, editor. Pasture Persistence Symposium. NZ Grassl Assoc Res Pract Ser. 15: 199-209.
Macfarlane MJ, Bonish PM. 1986. Oversowing white clover into cleared and unimproved North Island hill country - the role of management, fertiliser, inoculation, pelleting and resident rhizobia. Proc NZ Grassl Assoc. 47:43–51.
Malavalli MM, Hamid N, Kantono K, Liu Y, Seyfoddin A. 2021.. consumers' perception of in-vitro meat in New Zealand using the theory of planned behaviour model. Sustainability. 13:7430. doi:10.3390/su13137430.
Manderson AK, Mackay AD, Palmer AP. 2007. Environmental whole farm management plans: their character, diversity, and use as agri-environmental indicators in New Zealand. J Environtal Manage. 82:319–331.
Mark AF, Barratt BIP, Weeks E. 2013. Ecosystem services in New Zealand's indigenous tussock grasslands: conditions and trends. In: Dymond JR, editor. Ecosystem services in New Zealand – conditions and trends. Lincoln, New Zealand: Manaaki Whenua Press; p. 1–33.
McCahon AD, Ussher GR, McCahon KS. 2021. Diversified pastures at the front line of climate change in Northland: farmers experiences, new directions and wider implications for other parts of the country. In: Douglas G, editor. Resilient Pasture Symposium. NZ Grassl Assoc Res Pract Ser. 17: (in press).
McCaskill LW. 1963. A review of advances in tussock grassland. Proc NZ Grassl Assoc. 25:155–172.
McDowell R. 2017. Does variable rate irrigation decrease nutrient leaching losses from grazed dairy farming? Soil Use and Management. 33:530–537.
McDowell RW, Monaghan RM, Smith C, Manderson A, Basher L, Burger DF, Laurenson S, Pletnyakov P, Spiekermann R, Depree C. 2020. Quantifying contaminant losses to water from pastoral land uses in New Zealand III. What could be achieved by 2035? NZ J Agric Res. 21. doi:10.1080/00288233.2020.1844763.
McGlone MS. 1983. Polynesian deforestation of NewZealand: a preliminary synthesis. Archaeology Oceania. 18:11–25.
McGlone MS. 1989. The Polynesian settlement of New Zealand in relation to environmental and biotic changes. NZ J Ecol. 12(Supplement):115–130.
Mcgregor E, Mackay A, Dodd M, Kemp P. 1999. Silvopastoralism using tended poplars on New Zealand hill country: the opportunities. Proc NZ Grassl Assoc. 61:85–89.

McIvor SD, Aspin MD. 2001. R&D success stories and principles to practice. Proc NZ Grassl Assoc. 63:23–27.
McKenzie SA. 1980. The changing pattern of advisory work. Proc NZ Grassl Assoc. 42:191–193.
McLachlan JW, Becquer A, Haling RE, Simpson RJ, Flavel RJ, Guppy CN. 2021. Intrinsic root morphology determines the phosphorus acquisition efficiency of five annual pasture legumes irrespective of mycorrhizal colonisation. Functional Plant Biol. 48:156–170. doi:10.1071/FP20007.
McLeod A. 2011. World livestock 2011: livestock in food security FAO, Rome, Italy. [accessed 2021 November 7] http://www.fao.org/docrep/014/i2373e/i2373e00.htm.
McNally SR, Beare MH, Curtin D, Meenken ED, Kelliher FM, Pereira RC, Shen Q, Baldock J. 2017a. Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. Glob Change Biol. 23:4544–4555.
McNally SR, Laughlin DC, Rutledge S, Dodd MB, Six J, Schipper LA. 2017b. Herbicide application during pasture renewal initially increases root turnover and carbon input to soil in perennial ryegrass and white clover pasture. Plant Soil. 412:133–142.
McNeur AJ. 1953. Pasture measurement techniques as applied to strain testing. Proc NZ Grassl Assoc. 15:157–165.
McWethy DB, Whitlock C, Wilmshurst JM, McGlone MS, Fromont M, Li X, Dieffenbacher-Krall A, Hobbs WO, Fritz SC, Cook ER. 2010. Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. Proc Nat Acad Sci. USA. 107:21343–21348.
Mee JF, Rogers PAM, O'Farrell KJ. 1995. Effect of feeding a mineral-vitamin supplement before calving on the calving performance of a trace element deficient dairy herd. Vet Rec. 137:508–512.
Metherell AK. 1989. The cobalt enigma - some observations and strategies for Otago and southland. Proc NZ Grassl Assoc. 50:101–108.
Metherell AK, Owens JL, Moore GH, Mackintosh CG. 1996. Selenium supplementation alternatives for the South Island high country. Proc NZ Grassl Assoc. 58:199–204.
Mfe. 2016. Paris agreement: information on New Zealand's post-2020 commitment to reduce greenhouse gas emissions under the Paris Agreement. [accessed 2021 November 6] https://environment.govt.nz/what-government-is-doing/international-action/about-the-paris-agreement/.
Mills A, Moot DJ, McKenzie BA. 2006. Cocksfoot pasture production in relation to environmental variables. Proc NZ Grassl Assoc. 68:89–94.
Mills A, Thomson BC, Muir PD, Smith NB, Moot DJ. 2021. Resident hill country pasture production in response to temperature and soil moisture over 20 years in Central Hawke's Bay. In: Douglas G, editor. Resilient Pastures Symposium. NZ Grassl Assoc Res Pract Ser. 17: (in press).
Milne GD. 2006a. Technology transfer of novel ryegrass endophytes in New Zealand. In: Popay AJ, Thom ER, editors. 6th International Symposium on Fungal Endophytes of Grasses. NZ Grassl Assoc Res Pract Ser. 13: 237-239.
Milne GD, Shaw R, Powell R, Pirie B, Pirie J. 1997. Tall fescue use on dairy farms. Proc NZ Grassl Assoc. 59:163–167.
Min BR, Barry TN, Atwood GT, McNabb WC. 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. Animal Feed Sci Technol. 106:3–19.
Ministry for the Environment. 2004. Genetic modification - the New Zealand approach. Wellington (New Zealand): Ministry for the Environment. Publication number: ME 426: p. 29.
Ministry for the Environment. 2020. National policy statement for freshwater management 2020. Wellington, New Zealand: Ministry for the Environment. pp. 70.
Ministry for the Environment. 2021. Net emissions and removals from vegetation and soils on sheep and beef farmland. Wellington, New Zealand: Ministry for the Environment. Publication number: ME 1554: pp. 29.

Ministry of Primary Industries. 2021. Situation and outlook for primary industries, June 2021. Pp. 64. [accessed 2021 August 23] https://www.mpi.govt.nz/dmsdocument/45451-Situation-and-Outlook-for-Primary-Industries-SOPI-June-2021.

Mitchell KJ. 1945. Preliminary note on the use of ammonium molybdate to control whiptail in cauliflower and broccoli crops. NZ J Sci Technol. A. 27:287–293.

Moller H, Macleod CJ, Haggerty J, Rosin C, Blackwell G, Perley C, Meadows S, Weller F, Gradwohl M. 2008. Intensification of New Zealand agriculture: implications for biodiversity. NZ J Agric Res. 51:253–263.

Molloy B. 1977. The fire history. In: Knox GA, editor. The natural history of canterbury. Wellington, New Zealand: A. H. & A. W. Reed; p. 167–204.

Monaghan R, Manderson A, Basher L, Smith C, Burger D, Meenken E, McDowell R. 2021a. Quantifying contaminant losses to water from pastoral landuses in New Zealand I. Development of a spatial framework for assessing losses at a farm scale. NZ J Agric Res. 21. doi:10.1080/00288233.2021.1936572.

Monaghan R, Manderson A, Basher L, Spiekermann R, Dymond J, Smith C, Muirhead R, Burger D, McDowell R. 2021b. Quantifying contaminant losses to water from pastoral landuses in New Zealand II. The effects of some farm mitigation actions over the past two decades. NZ J Agric Res. 25. doi:10.1080/00288233.2021.1876741.

Monk S, Moot DJ, Belgrave B, Rolston MP, Caradus JR. 2016. Availability of seed for hill country adapted forage legumes. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 257-268.

Moorhouse AM, Westwood CT, Dumbleton AJ, Donnelly LP, Bridger LA. 1999. Effect of selenium applied to pasture on the selenium status of grazing sheep. Proc NZ Grassl Assoc. 61:69–73.

Moot DJ, Black A, Mills A. 2020. New Zealand drivers of pasture production and options available to improve composition and management. In: Growing with Grasslands. Proc. 61st Conference of Grassland Society of Southern Australia. Pp. 50-54.

Moot DJ, Brown HE, Teixeira E, Pollock K. 2003. Crop growth and development affect seasonal priorities for lucerne management. In: Moot DJ, editor. Legumes for dryland. NZ Grassl Assoc Res Pract Ser. 11: p. 201–208.

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

Moot DJ, Griffiths WM, Chapman DF, Dodd MB, Teixeira SP. 2021a. AgYields - a national database for collation of past, present and future pasture and crop yield data. In: Douglas G, editor. Resilient Pasture Symposium. NZ Grassl Assoc Res Pract Ser. 17: (in press).

Moot DJ, Yang X, Ta HT, Brown HE, Teixeira EI, Sim RE, Mills A. 2021b. Simplified methods for on-farm prediction of yield potential of grazed lucerne crops in New Zealand. NZ J Agric Res. doi:10.1080/00288233.2021.1909078.

Morris MC, Livesey JH. 2020. Survey: plant-based protein cost survey. Food New Zealand. 20:42–44. doi:10.3316/informit.445309398726174.

Morton JD, Gray MH, Gillingham AG. 2005. Soil and pasture responses to lime on dry hill country in central Hawke's Bay, New Zealand. NZ J Agric Res. 48:143–150.

Morton JD, Paterson DJ. 1982. Seasonal distribution of pasture production in New Zealand XVII. Kowhitirangi and Ahaura, West Coast, South Island. NZ J Exptal Agric. 10:245–252.

National Interest Analysis. 2016. The Paris agreement. [accessed 2021 November 6] https://www.parliament.nz/resource/en-NZ/51DBHOH_PAP69732_1/b3d874584455ca4c02251f71995b03d6f0aeee42.

Newsome PFJ. 1987. The vegetation cover of New Zealand. Water and Soil Miscellaneous Publication 112. Wellington, National Water and Soil Conservation Authority.

New Zealand Government. 2021. Resource management (National Environmental Standards for Freshwater) Regulations 2020. [accessed 18 June 2021] https://www.legislation.govt.nz/regulation/public/2020/0174/latest/whole.html#LMS364253.

New Zealand History Online: Impact of the War – NZ in the Korean War. [accessed 2021 April 11] https://nzhistory.govt.nz/war/korean-war/impact.

Norbury G, Heyward R, Parkes J. 2002. Short-term ecological effects of rabbit haemorrhagic disease in the short-tussock grasslands of the South Island, New Zealand. Wildlife Res. 29:599–604.
Nordmeyer AH, Davis MR. 1975. Legumes in high-country development. Proc NZ Grassl Assoc. 38:119–125.
Norton DA, Butt J, Bergin DO. 2018. Upscaling restoration of native biodiversity: a New Zealand perspective. Ecol Manage. Restorat. 19:26–35.
NZIER. 2014. Value of irrigation in New Zealand. NZIER report, Wellington. Pp. 64.
NZ Rhizobia. 2016. Taxonomy of New Zealand Native Legumes. [accessed 2021 July 21] https://www.rhizobia.co.nz/taxonomy/legume.
O'Connor KF. 1986. The influence of science on the use of tussock grasslands. Tussock Grassl Mountainlands Instit Rev. 43:15–78.
OECD. 2019. OECD Economic Surveys: New Zealand. [accessed July 21 2021] https://www.oecd.org/economy/surveys/new-zealand-2019-OECD-economic-survey-overview.pdf.
Palmer JC. 1999. Lowland Native Ecosystems — Key Elements in the Biodiversity Jigsaw. Proc. Royal NZ Instit. Hortic. Conf. 1-3rd October 1999. Pp 33-38. ISBN 0-9597756-3-3 http://www.rnzih.org.nz.
Pangborn MC, Woodford KB. 2011. Canterbury dairying - a study in land use change and increasing production. Proc. 18th Int. Farm Manage. Congr., Methven, Canterbury, New Zealand. Pp. 81-87.
Parker WJ. 2001. Future challenges for grassland farming. Proc NZ Grassl Assoc. 63:7–15.
Parker WJ, McCall DG. 1986. The importance of subdivision and management practices in improving hill country productivity. Proc NZ Grassl Assoc. 47:63–69.
Parminter TG. 1991. Financial evaluation of hill country pasture improvement. Proc NZ Grassl Assoc. 53:217–121.
Parsons AJ, Rowarth JS, Newton PCD. 2009. Managing pasture for animals and soil carbon. Proc NZ Grassl Assoc. 71:77–84.
Parsons AJ, Thornley JHM, Rasmussen S, Rowarth JS. 2017. Some clarification of the impacts of grassland intensification on food production, nitrogen release, greenhouse gas emissions and carbon sequestration: using the example of New Zealand. CAB Reviews 11 (054). [accessed 2021 August 24] doi:10.1079/PAVSNNR201611054.
Paterson JC. 1979. Implications of plant selectors' rights for herbage seed production - trade viewpoint. In: Lancashire JA, editor. Herbage seed production. NZ Grassl Assoc Res Pract Ser. 1: p. 116–118.
Perry GLW, Wilmshurst JM, McGlone MS, Napier A. 2012. Reconstructing spatial vulnerability to forest loss by fire in pre-historic New Zealand. Global Ecol Biogeography. 21:1029–1041.
Popay I, Field R. 1996. Grazing animals as weed control agents. Weed Technol. 10:217–231.
Post MJ. 2012. Cultured meat from stem cells: challenges and prospects. Meat Sci. 92:297–301.
Pottinger RP. 1968. Comments on the ecology of grass grub and porina caterpillar. Proc NZ Grassl Assoc. 30:102–113.
Powell CL, Bagyaraj DJ. 1984. VA mycorrhizae: why all the interest? In: Powell CL, Bagyaraj DJ, editors. VA Mycorrhiza. First edition. Boca Raton, FL: CRC press; p. 1–3.
Radcliffe JE. 1974a. Seasonal distribution of pasture production in New Zealand. I. Methods of measurement. NZ J Exptal Agric. 2:337–340. doi:10.1080/03015521.1974.10427692.
Radcliffe JE. 1974b. Seasonal distribution of pasture production in New Zealand. II. Southland plains. NZ J Exptal Agric. 2:341–348.
Radcliffe JE. 1975. Seasonal distribution of pasture production in New Zealand. IV. Westport and motueka. NZ J Exptal Agric. 3:239–246.
Ratajczak Z, Nippert JB, Ocheltree TW. 2014. Abrupt transition of mesic grassland to shrubland: evidence for thresholds, alternative attractors, and regime shifts. Ecol. 95:2633–2645. doi:10.1890/13-1369.1.
Reicosky DC, Saxton KE. 2006. Reduced environmental emissions and carbon sequestration. In: Baker CJ, Saxton KE, Ritchie WR, Chamen WCT, Reicosky DC, Ribeiro MFS, Justice SE,

Hobbs PR, editor. No-tillage seeding in conservation agriculture. Rome, Italy: FAO and CAB International; p. 257–267.
Reserve Bank of New Zealand. 2007. The Reserve Bank and New Zealand's Economic History. [accessed 2021 March 16] https://www.rbnz.govt.nz/-/media/ReserveBank/Files/Publications/Factsheets%20and%20Guides/factsheet-the-reserve-bank-and-nzs-economic-history.pdf.
Rickard DS, Radcliffe JE. 1976. Seasonal distribution of pasture production in New Zealand. XII. winchmore, Canterbury Plains dryland and irrigated pastures. NZ J Exptal Agric. 4:329–335.
Roberts AHC, Thomson NA. 1984a. Seasonal distribution of pasture production in New Zealand XVIII. South taranaki. NZ J Exptal Agric. 12:83–92.
Roberts AHC, Thomson NA. 1984b. Seasonal distribution of pasture production in New Zealand XVIV. central taranaki. NZ J Exptal Agric. 12:93–101.
Roberts AHC, White MD. 2016. From there to where? Past, present and future soil fertility management on hill country farms. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 127-136.
Rolleston WBR. 2016. Conditions for co-existence of genetic modification in a pasture based system – a farmer perspective. J. NZ Grassl. 78:83–88.
Rollo MD, Sheath GW, Slay MWA, Knight TL, Judd TG, Thomson NA. 1998. Tall fescue and chicory for increased summer forage production. Proc NZ Grassl Assoc. 60:249–253.
Rolston MP, Clifford PTP. 1989. Herbage seed: production and research - a review of 50 years. Proc NZ Grassl Assoc. 50:47–53.
Rolston MP, Lambert MG, Clark DA. 1982. Weed control options in hill country. Proc NZ Grassl Assoc. 43:196–203.
Rowarth J, Manning M, Roberts A, King W. 2020. New-generative agriculture - based on science, informed by research and honed by New Zealand farmers. J. NZ Grassl. 82:221–229.
Rowarth JS, Hampton JG, Hill MJ. 1998. Survival of the New Zealand herbage seed industry: quality is the answer. Proc Agron Soc NZ. 28:21–30.
Sanderson K, Webster M. 2009. Economic analysis of the value of pasture to the New Zealand economy. Report to Pasture Renewal Charitable Trust. Business and Economic Research Limited, BERL, Wellington, New Zealand. September 2009. Pp. 42.
Sargison ND, West DM, Clark RG. 1998. The effects of iodine deficiency on ewe fertility and perinatal lamb mortality. NZ Vet J. 46:72–75.
Saunders C, Saunders J. 2012. The Economic Value of Potential Irrigation in Canterbury. Report from Agribusiness and Economics Research Unit (AERU), Lincoln University. [accessed 2021 July 17] https://researcharchive.lincoln.ac.nz/handle/10182/6973.
Saunders JT, Greer G, Bourdôt G, Saunders C, James T, Rolando C, Monge J, Watt MS. 2017. The economic costs of weeds on productive land in New Zealand. Int J Agric Sustain. 15:380–392.
Saxby SH. 1934. Some observation on strain in grasses. Proc NZ Grassl Assoc. 3:7.
Saxby SH. 1947. Some grassland developments during the war and post war period. Proc. NZ Grassl. Assoc. 9:52–67.
Saxby SH. 1950. Tussock grassland associations. Proc NZ Grassl Assoc. 12:44–52.
Schipper LA, Mudge PL, Kirschbaum NU, Hedley CB, Golubiewski NE, Smaill SJ, Kelliher FM. 2017. A review of soil carbon change in New Zealand's grazed grasslands. NZ J Agric Res. 60:93–118.
Schipper LA, Parfitt RL, Fraser S, Littler RA, Baisden WT, Ross C. 2014. Soil order and grazing management effects on changes in soil C and N in New Zealand pastures. Agric., Ecosystems Environ. 184:67–75.
Scott D, Maunsell LA, Keoghan JM, Allan BE, Lowther KL, Cossens GG, editors 1995. A guide to pasture and pasture species for the New Zealand high country. NZ Grassl Assoc Res Pract Ser. 4.:41.
Scrimgeour F, Kumar V, Weenink G. 2017. Investment in covenanted land conservation. Institute for Business Research, University of Waikato. p. 40.
Scroggie MP, Parkes JP, Norbury G, Reddiex B, Heyward R. 2012. Lagomorph and sheep effects on vegetation growth in dry and mesic grasslands in Otago. New Zealand. Wildlife Res. 39:721–730.

Sexton AE, Garnett T, Lorimer J. 2019. Framing the future of food: the contested promises of alternative proteins. Nature Space. 2:47–72. doi:10.1177/2514848619827009.
Sheppard CS, Burns BR, Stanley MC. 2016. Future-proofing weed management for the effects of climate change: is New Zealand underestimating the risk of increased plant invasions? NZ J. Ecol. 40:398–405.
Sherlock R, Jewell P, Clough T. 2008. Review of New Zealand specific FRACGASM and FRACGASF emission factors. MAF Technical Paper No. 2011/32. Wellington, Ministry of Agriculture and Forestry.
Sherrell CG, Metherell AK. 1986. Diagnosis and treatment of molybdenum deficiency in pastures. Proc NZ Grassl Assoc. 47:203–209.
Singleton J. 2008. New Zealand in the nineteenth and twentieth centuries. EH.Net Encyclopedia, Whaples R, editor. February 10, 2008. http://eh.net/encyclopedia/an-economic-history-of-new-zealand-in-the-nineteenth-and-twentieth-centuries/.
Sithamparanathan J, Macfarlane MJ, Richardson S. 1986. Effect of treading, herbicides, season, and seed coating on oversown grass and legume establishment in easy North Island hill country. NZ J Exptal Agric. 14:173–182.
Smale MC, Dodd MB, Burns BR, Power IL. 2008. Long-term impacts of grazing on indigenous forest remnants on North Island hill country, New Zealand. NZ J Ecol. 32:57–66.
Smallfield PW. 1938. Review of topdressing in the Auckland province. Proc NZ Grassl Assoc. 7:1–12.
Smallfield PW. 1956. Techniques of land development in New Zealand. Proc NZ Grassl Assoc. 18:24–32.
Smith LC, Morton JD, Catto WD. 1999. The effects of fertiliser iodine application on herbage iodine concentration and animal blood levels. NZ J Agric Res. 42:433–440.
Smith NW, Fletcher AJ, Dave LA, Hill JP, McNabb WC. 2021. Use of the DELTA model to understand the food system and global nutrition. J Nutr. doi:10.1093/jn/nxab199.
Smith RG, Mather RDJ. 1985. Marketing herbage seeds. In: Burgess RE, Brock JL, editors. Using herbage cultivars. NZ Grassl Assoc Res Pract Ser. 3: p. 93–97.
Smyth SJ. 2017. Canadian regulatory perspectives on genome engineered crops. GM Crops Food. 8:35–43.
Springett JA. 1992. Distribution of lumbricid earthworms in New Zealand. Soil Biol Biochem. 24:1377–1381.
Squire JD. 1986. Subdivision: benefits and costs. Proc NZ Grassl Assoc. 47:71–75.
Stats NZ. 2021a. Irrigated land. [accessed 2021 August 28] https://www.stats.govt.nz/indicators/irrigated-land.
Stats NZ. 2021b. Farm number and size. [accessed 2021 November 6] https://www.stats.govt.nz/indicators/farm-numbers-and-size.
Steer MA, Norton DA. 2013. Factors influencing abundance of invasive hawkweeds, *Hieracium* species, in tall tussock grasslands in the Canterbury high country. NZ J. Bot. 51:61–70.
Stevens DR, Casey MJ, Cousins KA. 2016. Farming systems research: purpose, history and impact in New Zealand hill country. In: Thom ER, editor. Hill Country Symposium. NZ Grassl Assoc Res Pract Ser. 16: 67-86.
Stevens DR, Knowles I. 2011. Identifying the need for pasture renewal and valuing the contribution of renewal on a dairy farm – Telford Dairy, a case study. In: Mercer CF, editor. Pasture Persistence Symposium. NZ Grassl Assoc Res Pract Ser. 15: 211-216.
Stevens EJ, Baker CJ, Mayer M, Hill M, Yunlai X. 2000. International seed industry and food production potential of NZ small- and medium-scale direct drilling technologies. ICETS2000, Beijing, PR China (11-13 October) Session 6: Technology Innovation and Sustainable Agriculture - Supporting technologies to seed industries (www.icets2000.ac.cn); p. 13.
Stewart AV. 2005. The potential for domestication and seed propagation of native New Zealand grasses for turf. Royal New Zealand Institute of Horticulture (Inc.). Greening the City. ISBN 0-959-77566-8; p. 277–284.
Stewart AV. 2006. Genetic origins of perennial ryegrass (*Lolium perenne*) for New Zealand pastures. In: Mercer CF, editor. 'Breeding for Success: Diversity in Action'. Proc. 13th

Australasian Plant Breeding Conference, Christchurch, New Zealand 18-21 April 2006; p. 11–20.
Stokes S, Macintosh KA, McDowell RW. 2021. Reflecting on the journey of environmental farm planning in New Zealand. NZ J Agric Res. doi: 10.1080/00288233.2021.1876108.
Suckling DM. 2013. Benefits from biological control of weeds in New Zealand range from negligible to massive: a retrospective analysis. Biolog Contr. 66:27–32.
Suckling FET. 1951. Results of recent experiments on surface sowing. Proc NZ Grassl Assoc. 13:119–126.
Suckling FET. 1959. Pasture management trials on unploughable hill country at te Awa II. results for 1951–57. NZ J Agric Res. 2:488–543.
Sustainable Nutrition Initiative. [accessed August 28 2021] https://sustainablenutritioninitiative.com/.
Suttie NF. 2010. Mineral nutrition of livestock, 4th ed. London, UK: CABI; p. 565 doi:10.1079/9781845934729.0000
Taylor AR. 1974. Irrigation production and design techniques. Proc NZ Grassl Assoc. 36:30–38.
Taylor AR, Aldridge DG, Kermode IM. 1985. Farm design for efficient irrigation. Proc NZ Grassl Assoc. 46:31–36.
Te Ara. 2008a. Story: Ngā tupu mai i Hawaiki – plants from Polynesia. [accessed 2021 July 21] https://teara.govt.nz/en/nga-tupu-mai-i-hawaiki-plants-from-polynesia.
Te Ara. 2008b. Story: Agricultural education. [ accessed 2021 August 28] https://teara.govt.nz/en/agricultural-education/page-7.
Tebb CP. 1959. Evaluation of economic aspects of aerial topdressing. Proc NZ Grassl Assoc. 21:58–67.
Thom ER, Fraser TJ, Hume DE. 2011. Sowing methods for successful pasture establishment – a review. In: Mercer CF, editor. Pasture Persistence Symposium. NZ Grassl Assoc Res Pract Ser. 15: 31-38.
Thomas SM, Bloomer D, Martin RJ, Horrocks A. 2006. Spray irrigation on dairy pastures – efficient or not? Proc NZ Grassl Assoc. 68:177–181.
Tomasetto F, Casanovas P, Brandt SN, Goldson SL. 2018a. Biological control success of a pasture pest: Has Its parasitoid lost its functional mojo? Front Ecol Evol. 6:215. doi: 10.3389/fevo.2018.00215.
Tomasetto F, Cianciullo S, Reale M, Attorre F, Olaniyan O, Goldson SL. 2018b. Breakdown in classical biological control of Argentine stem weevil: a matter of time. BioControl. 2018:1–11. doi:10.1007/s10526-018-9878-4.
Tomasetto F, Tylianakis JM, Realed M, Wratten S, Goldson SL. 2017. Intensified agriculture favors evolved resistance to biological control. Proc Nat Acad Sci. 114:3885–3890.
Tozer KN, Bourdôt GW, Edwards GR. 2011b. What factors lead to poor pasture persistence and weed ingress? In: Mercer CF, editor. NZ Grassl Assoc Res Pract Ser. 15:129–138.
Tozer KN, Cameron CA, Thom ER. 2011a. Weed ingress and pasture persistence in Bay of Plenty dairy farms: field observations and farmer perceptions. Proc. NZ Plant Protection. 64:68–74.
Tozer KN, Douglas GB. 2016. Pasture establishment on non-cultivable hill country: a review of the New Zealand literature. In: Thom ER, editor. Hill Country Symposium. NZ Grassl. Assoc Res Pract Ser. 16: 213-224. doi:10.3389/fsufs.2021.550334.
Tozer KN, Rennie GM, King WM, Mapp NR, Aalders LT, Bell NL, Wilson DJ, Cameron CA, Greenfield RM. 2015. Pasture renewal on Bay of Plenty and Waikato dairy farms: impacts on pasture performance post-establishment. NZ J. Agric. Res. 58:241–258.
Tran DX, Pearson D, Palmer A, Gray D. 2020. Developing a landscape design approach for the sustainable land management of hill country farms in New Zealand. Land. 9:185. doi:10.3390/land9060185.
Tucker C. 2018. Using environmental imperatives to reduce meat consumption: perspectives from New Zealand. Kōtuitui: NZ J Soc Sci Online. 13:99–110. doi:10.1080/1177083X.2018.1452763.
Ulyatt MJ. 1970. Evaluation of pasture quality under New Zealand conditions. Proc NZ Grassl Assoc. 32:61–68.
United Nations. 2020. About the sustainable development goals. [accessed 2020 April 16] https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

van der Weerden TJ, Laurenson S, Vogeler I, Beukes PC, Thomas SM, Rm R, Topp CFE, Lanigan G, de Klein CAM. 2017. Mitigating nitrous oxide and manure-derived methane emissions by removing cows in response to wet soil conditions. Agric Syst. 156:126–138. doi:10.1016/j.agsy.2017.06.010.

van Selm B, de Boer IJM, Ledgard SF, van Middelaar CE. 2021. Reducing greenhouse gas emissions of New Zealand beef through better integration of dairy and beef production. Agric. Systems. 186:102936. doi:10.1016/j.agsy.2020.102936.

Waghorn GC. 2008. Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production - progress and challenges. Animal Feed Sci Technol. 147:116–139.

Waghorn GC, Clark DA. 2004. Feeding value of pastures for ruminants. NZ Vet. J. 52:320–331.

Waghorn GC, McNabb WC. 2003. Consequences of plant phenolic compounds for productivity and health of ruminants. Proc. Nutr. Soc. 62:383–392.

Wall AM, Goodrich JP, Schipper LA. 2021. Importance of resilient pastures for New Zealand's agricultural soil carbon stocks. In: Douglas G, editor. Resilient Pasture Symposium. NZ Grassl Assoc Res Pract Ser. 17: (in press).

Wang O, Scrimgeour F. 2021. Willingness to adopt a more plant-based diet in China and New Zealand: applying the theories of planned behaviour, meat attachment and food choice motives. Food Qual Preference 93. doi:10.1016/j.foodqual.2021.104294

Watkin BR. 1974. The performance of pasture species in Canterbury. Proc NZ Grassl Assoc. 36:180–190.

Watkinson JH. 1989. Effect of controlled-release selenium granules applied with fertiliser on blood levels of grazing sheep. Proc NZ Grassl Assoc. 50:95–99.

Watson RN, Mercer CF. 2000. Pasture nematodes: the major scourge of white clover. Proc NZ Grassl Assoc. 62:195–199.

Welten BG, Ledgard SF, Balvert SF, Kear MJ, Dexter MM. 2016. Effects of oral administration of dicyandiamide to lactating dairy cows on residues in milk and the efficacy of delivery via a supplementary feed source. Agric. Ecosystems Environ. 217:111–118.

Whitehead D. 2020. Management of grazed landscapes to increase soil carbon stocks in temperate, dryland grasslands. Frontiers in Sustainable Food Systems. 4: 4. Article 585913. doi: 10.3389/fsufs.2020.585913

Whitehouse NJ, Smith D. 2010. How fragmented was the British holocene wildwood? Perspectives on the "Vera" grazing debate from the fossil beetle record. Quaternary Sci Rev. 29:539–553.

Whitmore FW. 1979. Implications of plant selectors' rights for herbage seed production - plant varieties office viewpoint. In: Lancashire JA, editor. Herbage seed production. NZ Grassl Assoc Res Pract Ser. 1; p. 112–115.

Wichtel JJ. 1994. Selenium in New Zealand dairy cattle: recent developments. In: Mineral nutrition. veterinary continuing education. Palmerston North, New Zealand: Massey University, Publication No. 137; p. 35–61.

Wichtel JJ, Craigie AL, Varela-Alvarez H, Williamson NB. 1994. The effect of intra-ruminal selenium pellets on growth rate, lactation and reproductive efficiency in dairy cattle. NZ Vet J. 42:205–210. doi:10.1080/00480169.1994.35824.

Widdowson JP, Walker JW. 1971. Effects of lime and molybdenum on the yield and composition of white clover in a sequence of New Zealand zonal soils. NZ J Agric Res. 14:801–820.

Wilkie DR. 1954. Role of soil and water conservation in, grassland production. Proc. NZ Grassl Assoc. 16:157–165.

Wilkinson AG. 1999. Poplars and willows for soil erosion control in New Zealand. Biomass Bioenergy. 16:263–274.

Wilks M, Phillips CJ. 2017. Attitudes to in vitro meat: a survey of potential consumers in the United States. PLoS ONE. 12:e0171904.

Williams PH, Haynes RJ. 1990. Influence of improved pastures and grazing animals on nutrient cycling within New Zealand soils. NZ J Ecol. 14:49–57.

Williams WM, Easton HS, Jones CS. 2007. Future options and targets for pasture plant breeding in New Zealand. NZ J Agric Res. 50:223–248.

Willocks MJ. 1999. Commercialisation of genetically modified crops in New Zealand. Proc NZ Grassl Assoc. 61:117–119.
Willoughby BE, Barns SA. 2002. Tropical grass webworm (*Herpetogramma licarsisalis*): Implications for dairy farming in Northland. Proc NZ Plant Prot. 55:30–36.
Wilmshurst JM, Anderson AJ, Higham TFG, Worthy TH. 2008. Dating the late prehistoric dispersal of polynesians to New Zealand using the commensal Pacific rat. Proc Natl Acad Sci. USA. 105:7676–7680.
Wilmshurst JM, Hunt TL, Lipo CP, Anderson AJ. 2011. High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia. Proc Natl Acad Sci. USA. 108:1815–1820.
Winichayakul S, Beechey-Gradwell Z, Muetzel S, Molano G, Crowther T, Lewis S, Xue H, Burke J, Bryan G, Roberts NJ. 2020. In vitro gas production and rumen fermentation profile of fresh and ensiled genetically modified high–metabolizable energy ryegrass. J Dairy Sci. 103:2405–2418.
Woodfield DR. 2002. Presidential address: The importance of agricultural research to New Zealand's future. Proc NZ Grassl Assoc. 64:1–5.
Woodfield DR, Clark DA. 2009. Do forage legumes have a role in modern dairy farming systems? Irish J Agric Food Res. 48:137–147.
Woodfield DR, Roldan MB, Voisey CR, Cousins GR, Caradus JR. 2019. Improving environmental benefits of white clover through condensed tannin expression. J NZ Grassl. 81:195–202.
Woodward SL, Waghorn GC, Laboyrie PG. 2004. Condensed tannins in birdsfoot trefoil (*Lotus corniculatus*) reduce methane emissions from dairy cows. Proc, NZ Soc. Animal Prod. 64:160–164.
Worsley K. 1999. Pest plants and their control. New Zealand plants and their story. Proceedings of the Royal New Zealand Institute of Horticulture Conference 1-3 October 1999. Pp 29-32. ISBN 0-9597756-3-3 http://www.rnzih.org.nz.
Young RG, Smart G, Harding JS. 2004. Impacts of hydro-dams, irrigation schemes and river control works. In: Harding JS, Mosley P, Pearson C, Sorrell R, editor. Freshwaters of New Zealand. Christchurch: Caxton Press; p. 37.1–37.16.
Yule I, Pullanagari R, Irwin M, McVeagh P, Kereszturi G, White M, Manning M. 2015. Mapping nutrient concentration in pasture using hyperspectral imaging. J NZ Grassl. 77:47–50.
Zydenbos SM, Barratt BIP, Bell NL, Ferguson CM, Gerard PJ, McNeill MR, Phillips CB, Townsend RJ, Jackson TA. 2011. The impact of invertebrate pests on pasture persistence and their interrelationship with biotic and abiotic factors. In: Mercer CF, editor. Pasture Persistence Symposium. NZ Grassl Assoc Res Pract Ser. 15:109–118.