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Perspectives on pasture establishment in New Zealand dairy systems: challenges, innovations, and agroecological implications

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The productivity and persistence of pasture species in Aotearoa New Zealand (NZ) are crucial for pastoral systems including the dairy, sheep, and beef industries and are predominantly based on perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). Increasingly, farmers are exploring other simple grass/legume mixtures and also incorporating mixed species swards. This perspective paper critically examines the methods and challenges associated with pasture establishment, focusing on seed germination, sowing techniques, and post-establishment management. It discusses the influence of environmental factors including soil type, moisture, and temperature on seed germination and seedling persistence, alongside the impact of grazing practices on pasture longevity. Economic considerations and environmental impacts of various establishment methods, including overgrazing, chemical termination, and direct drilling, are examined. This perspective paper also covers the integration of new technologies such as precision agriculture, robotics, and advanced seed genetics, noting barriers to their adoption. From an agroecological perspective, we argue for a systems-based approach that integrates biodiversity, farmer knowledge, and long-term resilience into pasture renewal strategies. We also identify research gaps related to species persistence, climate adaptation, and policy support, and call for collaborative innovation to ensure the future productivity and ecological integrity of NZ pastoral system. Lastly, the paper highlights the need for further research into long-term pasture performance, species persistence, and the effectiveness of emerging technologies to optimise pasture management in NZ changing climate.

KEYWORDS

grazing management, overgrazing, oversowing, pasture performance, pasture renewal

1 Introduction

The productivity and persistence of pasture species in Aotearoa New Zealand (NZ) are fundamental to the continued success of the pastoral industries (dairy, beef, sheep and deer). Perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) typically dominate, although increasingly, other simple grass/legume mixtures as well as swards of mixed pasture species are used. These include, but are not limited to, annual (*L. multiflorum* Lam.) and hybrid ryegrasses (*L.* × *boucheanum* Kunth) (Easton et al., 1997), cocksfoot (*Dactylis glomerata* L.) (McCahon et al., 2021), prairie grass [*Bromus catharticus* Vahl (Watkin, 1974; Baars and Cranston, 1977), *B. willdenowii* Kunth (Crush et al., 1989; Stewart, 1996), *B. valdivianus* Phil. (Stewart, 1996; Ordóñez et al., 2021)], Timothy (*Phleum pratense* L.) (Charlton and Stewart, 2000), red clover (*T. pratense* L.) (Brougham, 1959), lucerne (*Medicago sativa* L.) (Allen et al., 2011), plantain (*Plantago lanceolata* L.) (Al-Marashdeh et al., 2021), tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh.], and chicory (*Cichorium intybus* L.) (Rollo et al., 1998), and are becoming more common, depending on topography, environmental conditions, and production goals. However, over time, declining pasture performance due to overgrazing (including selective and preferential grazing, coupled with treading), disruption of nutrient cycles, environmental stress (extreme events like flooding and drought), and pest and disease pressure (Daly et al., 1999; Bell et al., 2011; Parsons et al., 2011; Stevens and Knowles, 2011; Tozer et al., 2011) threaten the long-term persistence, productivity, and quality of pastoral grazing systems in NZ. This degradation often necessitates pasture renewal (also termed renovation, re-seeding or restoration) to maintain or enhance pasture productivity or to alter pasture composition (Cartmill and Donaghy, 2024).

Methods of pasture establishment vary by operation and conditions (climate, topography, soil, etc.) and include oversowing, direct drilling into terminated pasture (using herbicide, overgrazing, and/or tillage) or following a forage or row crop (Campbell and Kunelius, 1984; Kerr et al., 2015; Belyaeva et al., 2016; Rutledge et al., 2017). However, there are distinct research gaps around pasture establishment, particularly in understanding the long-term effects, comparisons across different soil types, and the economic viability, of various establishment methods (Fraser et al., 2014; Cartmill and Donaghy, 2024). In particular, studies have often failed to provide comprehensive data on the persistence of pasture species relative to establishment methods, with Bartholomew (2005) suggesting no clear effect of establishment method on species persistence. This indicates that an array of interrelated, dependent, and independent factors influence pasture establishment, including topography, soil type, seed bed preparation, plant species, seeding rate, planting depth, time of sowing (season), climate, irrigation availability, and pasture and grazing management.

This perspective paper aims to evaluate the methods of pasture establishment in NZ pastoral systems, synthesizing current knowledge (Figure 1) and identifying critical gaps for future research. There is a focus on the dairy industry, as that is where research has focused the most, but findings are transferrable to other pastoral industries. Here we argue that pasture establishment should be viewed through a

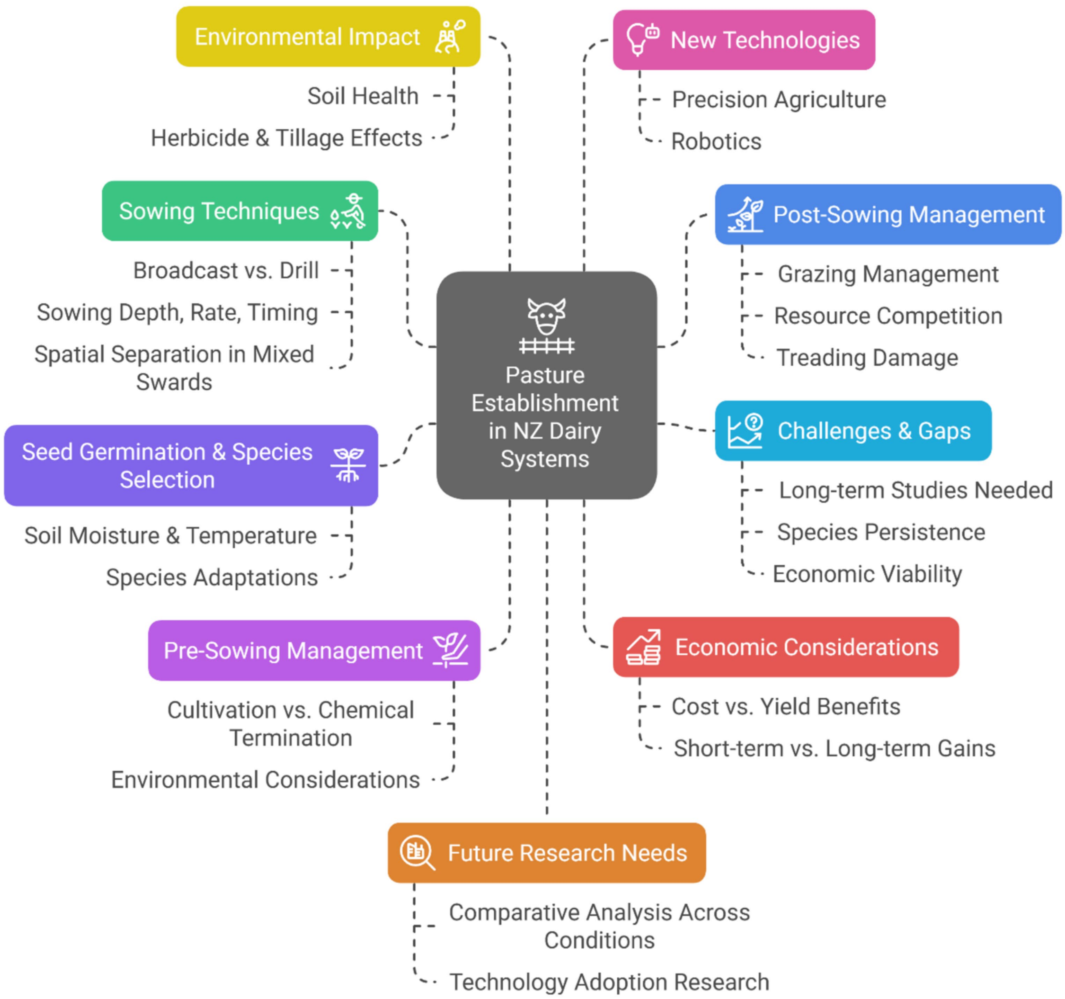

FIGURE 1
Key factors, challenges, and research gaps in pasture establishment in Aotearoa New Zealand (NZ) dairy systems.

'systems lens', one that incorporates ecological resilience, technological innovation, and farmer experience. We highlight critical gaps in current research, examine underutilized tools and approaches, and reflect on the need to align establishment practices with agroecological principles. Our aim is not to provide an exhaustive review, but to stimulate discussion around how we establish pasture systems to support long-term sustainability and resilience in NZ, given a changing climate and production landscape, with insights transferable to other temperate climates. Specifically, this paper seeks to address the lack of long-term studies, the need for comparative analyses across different environmental conditions, and the economic assessments of pasture establishment practices.

2 Background and challenges in pasture establishment

Pasture establishment is a complex, multistage process shaped by biological, environmental, and management interactions. Bellotti and Blair (1989a) describe three distinct phases for pasture establishment: (i) seed germination, (ii) seedling emergence, and (iii) seedling survival and growth into a productive and persistent sward. These general phases can be further refined according to the specific pasture species, which starts the groundwork for successful pasture development. However, pasture establishment success varies significantly depending on soil characteristics, climate, plant traits, and farming practice. Furthermore, despite decades of research, challenges in pasture establishment remain persistent and poorly resolved. Seed losses can be substantial, for example Brock and Thomas (1991) estimated that 50–90% of sown seed may fail to establish in the first year. Factors such as soil type, seedbed quality, sowing depth, seeding rate, and sowing method (e.g., broadcast, drill, oversown) all interact to determine outcomes, but few studies evaluate how these variables are integrated in the long term. The influence of sowing time especially under increasingly erratic seasonal conditions (climate variability), further complicates on-farm decision-making. Whilst physical impacts, including desiccation, seed predation, and herbivory have long been acknowledged (Fenner, 2012), they are often oversimplified in practical models of pasture establishment and may be mitigated with application of agronomic best management practices, for example tillage, along with application of fertilisers, herbicides, insecticides, and irrigation.

There is also a critical disconnect between research emphasis and farmer priorities, with much of the literature focused on early-stage establishment success under controlled conditions, yet long-term persistence under real-world grazing (and treading) remains poorly understood. For example, Thom et al. (2011) considered establishment successful if sown species survive for at least 1 year, whilst Tozer et al. (2016) defined it as the ability of these species to set seed. These varying definitions reflect broader inconsistencies in how establishment is measured, and raise questions around what we are actually optimising, initial coverage or long-term system function? As Bellotti and Blair (1987) highlighted nearly four decades ago, the survival of emerged seedlings remains a noticeable gap in pasture research. This 'knowledge gap' is especially problematic under grazing, where selective defoliation, treading, and/or nutrient cycling disruptions create feedback that influence species survival and pasture resilience. Yet such dynamics are rarely included in establishment studies. Here we argue that pasture establishment must be viewed not simply as a seeding event, but as an ecological process nested within broader grazing system dynamics; one that is affected by soil health, climate variability, and farmer decision-making. We suggest that this broader view would offer farmers more comprehensive guidance on how to achieve and maintain productive pastures over time and refine the 'trigger' point for pasture renewal.

3 Pre-sowing management: Balancing establishment and system resilience

Pre-sowing management practices in NZ vary widely depending on enterprise type, species mix, and site conditions. Common approaches include overgrazing (mostly grazing close to the ground), chemical termination, full cultivation, direct drilling, and under- or oversowing without prior termination. Whilst these methods aim to reduce competition from existing swards and create favourable conditions for seedling establishment, their long-term impacts on soil structure, ecosystem processes, and pasture resilience are often underexamined.

Cultivation, for example, can offer a 'clean' seedbed and result in good early establishment (Bellotti and Blair, 1989b), but repeated tillage may degrade soil physical properties, increase compaction, disrupt aggregate stability, and accelerate organic matter (OM) loss. These changes reduce infiltration and root penetration, increasing vulnerability to erosion, along with drought susceptibility, key risks under changing climate conditions. Similarly, whilst chemical termination via herbicides can efficiently suppress existing vegetation and reduce competition (Bartholomew, 2005; Glassey et al., 2013), it raises concerns around residual soil effects, runoff, and biodiversity loss (Arias-Estévez et al., 2008; Fenoll et al., 2011). Direct drilling is often seen as a compromise that retains soil structure whilst reducing establishment costs and disturbance. Yet it can be less effective in compacted or heavy soils, and success may depend on species selection, soil moisture, and machine size and precision (Morris et al., 2010; Chamen et al., 2015). Whilst overgrazing to suppress existing swards is low cost and less disruptive to soil or sward structure, it can lead to uneven suppression (i.e., selective grazing of more palatable species and no grazing of weed species), variable seed-soil contact, and animal welfare concerns if not managed carefully.

What we feel is often missing in discussions of pre-sowing management is a broader systems perspective. In that, decisions are typically driven by short-term goals, including cost, ease, and immediate establishment success, rather than long-term soil health and/or resilience. In our view, evaluating these practices through an 'agroecological lens' is crucial. For example, how do the practices affect soil microbial activity, nutrient cycling, and/or the system's ability to recover from climatic extremes (drought and flooding)? How well do these practices support a transition towards more diverse and resilient pasture systems? These questions are particularly relevant in NZ intensively managed dairy landscapes, where repeated pasture renewal may lead to 'system fatigue' and mask deeper issues in grazing pressure, fertility management, and/or soil degradation. Therefore, rather than viewing pre-sowing management as a technical problem with a fixed solution, we argue that it should be treated as a strategic 'intervention point', which can either reinforce or undermine long-term sustainability, depending on how and when it is applied.

3.1 Chemical termination and environmental impacts: Navigating complex trade-offs

Chemical termination, most commonly using glyphosate-based herbicides, followed by direct drilling, is a widely adopted strategy for pasture renewal in NZ. It is often favoured over conventional tillage for its potential to reduce soil disturbance and associated carbon (C) and nitrogen (N) losses, especially on NZ erosion-prone landscapes (Aslam et al., 2000; Baker et al., 2007). However, the environmental footprint of herbicide use is not straightforward. For example, concerns remain over herbicide residues, their variable effects on seed germination across species, and broader impacts on soil biota and nutrient dynamics (Havens et al., 2017; Helander et al., 2019). For example, the impact of herbicide residues on seed germination is inconsistent across species, depending on seed size, germination type (epigeal vs. hypogeal), and soil adsorption dynamics. For example, species with larger seeds may tolerate residues better than small-seeded grasses (Helander et al., 2019). Adjusting sowing time post-application or selecting tolerant species may mitigate these effects, however this may reduce pasture productivity or shorten growing seasons. Similarly, whilst herbicide residues may improve phosphorus (P) availability due to shared soil adsorption sites (Rose et al., 2018), this benefit can come at the cost of increased P leaching, particularly on sloping or poorly structured soils.

Chemical termination affects resistance management, where residual herbicides may suppress target plants whilst giving competitive advantage to resistant weed species (Gomes et al., 2017), potentially compromising establishment and increasing chemical reliance over time. Moreover, sublethal exposure to herbicides can disrupt plant hormone signalling, which may make young seedlings more susceptible to disease and herbivory (Martinez et al., 2018; Singh et al., 2020).

From a soil health perspective, chemical termination is often promoted as a conservation practice, yet we feel that this claim merits closer scrutiny. Whilst it potentially avoids the compaction and aggregate disruption associated with full cultivation, the long-term effect on soil OM remains uncertain. Terminated pastures can contribute large inputs of C via decomposing roots and residues (McNally et al., 2017), but this may be offset by reduced photosynthesis and increased microbial respiration, leading to short-term C losses (Rutledge et al., 2014). However, manure application at the time of cultivation as part of the renewal process may partially offset these C losses (Wall et al., 2024). The extent to which these systems recover or build C over time depends heavily on the 'speed' and quality of re-establishment, which reflects a variable seldom tracked in pasture trials (Paustian et al., 2000). Nitrogen dynamics are similarly complex. Whilst legume-rich pastures increase soil N and reduce N fertiliser needs (Ledgard et al., 2001), termination increases the risk of N losses, through both leaching and gaseous nitrous oxide (N_2O) emissions (Belyaeva et al., 2016). These risks are amplified on wet soils and/or with high rainfall, and current management strategies rarely account for more detailed timing of termination, which for example, consider species composition and/or site hydrology. Finally, the presence of terminated plant residues may serve as both a barrier and a buffer. Surface litter can insulate the soil and reduce light and moisture penetration, hindering seedling emergence. It may also protect (insulate) against erosion, frost, and rapid drying. Therefore, these trade-offs need to be considered in context, rather than assuming that residues are inherently beneficial or problematic.

In our view, chemical termination decisions must move beyond a simplistic binary of 'disturbance versus conservation.' Instead, they should be framed at the farm scale as multifactorial choices, which are influenced by pasture species, soil, rainfall, weed pressure, and on-farm priorities. Current research rarely integrates these variables in a way that reflects real-world decision-making. To improve sustainability, we argue for a shift towards adaptive, site-specific decision frameworks that incorporate herbicide impacts into broader agroecosystem planning, not just immediate establishment success.

3.2 Overgrazing and fire management: Low-input strategies with complex trade-offs

In the search for lower-cost or lower-input alternatives to chemical or mechanical termination, some pasture systems in NZ have explored the use of strategic overgrazing to suppress existing vegetation and promote seed-soil contact. In international contexts, prescribed burning has also been used, although it remains uncommon in NZ pastoral systems. Whilst both strategies offer potential benefits, they come with ecological costs and uncertainties that require careful consideration.

Overgrazing, where grazing livestock at high stocking density are intentionally allowed to reduce vegetative cover, can be a practical alternative to herbicide application, especially where chemical use is restricted or cost-prohibitive (Robinson and Dowling, 1985). However, the sustainability of this approach hinges on site-specific variables such as stocking density, grazing duration, soil type, and 'historical' land use. Overgrazing can lead to increased soil compaction, reduced soil porosity, lower infiltration rates, and ultimately, reduced root biomass and low soil C stocks (Greenwood and McKenzie, 2001; Derner and Schuman, 2007). These impacts may initiate system feedback loops, where declining soil structure, particularly on sloped or fragile soils where erosion risk is already high, leads to a decline in pasture productivity and persistence (Greene et al., 1994; Silburn et al., 2011). In that, whilst overgrazing is often framed as a cost-saving and transitional strategy, its use as a pasture establishment tool may undermine the very resilience and soil functions that pasture renewal is intended to improve. In this context, we argue that overgrazing should not be treated as a 'neutral management technique', but rather as an intervention of last resort, requiring tight control and rapid post-treatment recovery plans.

Prescribed burns (fire), by contrast, are well studied in rangeland systems globally, yet their role in temperate pasture systems in NZ remains marginal, possibly reflecting the 'moist' temperate climate and common high winds. Fire can suppress dominant vegetation, stimulate regrowth, and reduce pest pressure, with some evidence suggesting its usefulness for spatially redistributing grazing pressure (Fuhlendorf and Engle, 2001; Vermeire et al., 2004). However, fire impacts on soils are highly variable. High-temperature burns can induce soil water repellence, degrade soil structure, and accelerate erosion and nutrient loss, particularly where organic horizons are shallow or soil moisture is low (DeBano, 2000; Neary and Leonard, 2020). The ecological outcome of fire also depends on burn frequency, fuel load, soil properties, and landscape context. Repeated burning can deplete soil N, reduce microbial activity, and alter OM composition (Ojima et al., 1994; Girona-García et al., 2018). In heavily grazed systems, the interaction between fire and grazing can amplify degradation unless followed by appropriate recovery periods (O'connor et al., 2004; Gordijn and O'Connor, 2021).

From a systems perspective, both overgrazing and fire present non-chemical options for sward suppression, but their ecological trade-offs are often underappreciated. In NZ, where pastoral systems face rising scrutiny over soil health, greenhouse gas (GHG) emissions, and biodiversity, these approaches must be evaluated not just by short-term establishment success, but by their long-term impact on agroecosystem functions and resilience. We suggest that if employed at all, fire and overgrazing should be framed as strategic, transitional tools, not default practices, and should be integrated into a broader agroecological transition strategy that includes rest periods, species diversification, and soil monitoring. There is currently limited research in NZ that examines these options holistically and we feel this represents a clear gap in the pasture renewal discourse and one which deserves greater attention.

4 Sowing strategies and methods

4.1 Seed coat treatment: Customization and caution

Advances in seed coating technologies are reshaping plant establishment strategies globally, with treatments, ranging from simple nutrient coatings to complex 'banding' of bioactive formulations and synthetics chemicals, which are marketed as tools for improved seedling survival, enhanced pest and disease resistance, and as an effective means of delivering inoculants at sowing (Afzal et al., 2020; Berto et al., 2021; Javed et al., 2022). Seed coat treatments may also improve flowability in modern sowing equipment, supporting the adoption of precision drilling in increasingly variable soil conditions.

As NZ pasture systems face greater pressures from climate variability, pest adaptation, and soil degradation, 'prescriptive seed treatments' offer the possibility of tailoring sowing to mitigate micro-environmental constraints such as low fertility, drought risk, and pathogen load. We envision a future in which pasture seed mixes are coated with site-specific consortia of growth-promoting microbes, polymer matrices for water retention, synthetic nutrient boosters, and beneficial microbes which provide farmers with targeted, climate-resilient tools to enhance pasture establishment and performance. However, we feel that this growing enthusiasm for seed coating technology should be tempered by critical reflection and a certain degree of caution. In that, current commercially available seed treatments have been subjected to limited independent assessment under NZ conditions and across the range of soil types, moisture regimes, and grazing intensities found in pastoral systems here. In addition, the long-term effects of some seed coatings on 'native' soil microbial ecology, residue breakdown, and pasture-animal interactions remain poorly understood. Some bio-coatings may persist in soils longer than expected, interfering with future crops and potentially masking microbial community shifts and losses. Furthermore, accessibility and cost may limit widespread adoption. Highly tailored pasture seed treatments may become accessible only to well-capitalised farms or large-scale seed retailers, leaving smaller producers and less mainstream practitioners (e.g., organic, regenerative) reliant on relatively untreated seed. There is also potential for seed treatment technologies to narrow genetic diversity within a sown pasture, by favouring a limited range of 'treatment-compatible' pasture species.

We argue that pasture seed coating treatments should not be viewed as a 'silver bullet', but as part of a broader strategy to improve establishment under site-specific constraints. For the technology to support sustainability and equity goals, independent research and evaluation is needed to clarify potential ecological impacts, efficacy across diverse farm systems, and/or cost–benefit relationships under real-world grazing conditions. We feel that prescriptive seed coatings could be transformative for NZ pasture establishment, but only if deployed transparently, equitably, and as part of an integrated agroecological framework, which is yet to be fully developed and tested.

4.2 Sowing methods: Adaptation over optimization

The choice of sowing method, whether broadcast, direct drilling, or frost seeding, is often framed in terms of maximising seedling emergence or pasture biomass. However, we suggest that performance differences among methods are strongly context-dependent, and are shaped by a variety of on-site constraints, including topography, soil fertility, machinery access, and climatic variability. Even with these constraints, seed sowing is still complex, particularly when using even simple mixes of seed. For example, direct drilling is widely regarded as a superior method for ensuring seed-to-soil contact, and as a means of protecting seeds from desiccation, and controlling planting depth (Taylor et al., 1972; Campbell, 1985). For example, lucerne and white clover typically show stronger emergence and biomass accumulation when direct drilled compared to broadcast (Mueller and Chamblee, 1984; Byers and Templeton, 1988). However, these advantages may be outweighed by limitations in terrain, equipment availability, or soil compaction risk, especially on steep hills or in remote, low-capital systems. Broadcast seeding, by contrast, often results in lower and more variable emergence due to environmental stresses (Taylor et al., 1969), but may offer greater flexibility. For example, broadcasting is well suited to inaccessible terrain or less-mechanised farms and may achieve 'adequate results' where seed-soil contact is improved through subsequent grazing, harrowing, or rainfall. Frost-seeding, whereby seed is broadcast onto frozen ground, can facilitate seed incorporation through natural freeze–thaw cycles and has proven effective in temperate climates with cold winters (Casler et al., 1999; Känkänen et al., 2001).

These sowing method examples illustrate a broader point, that no sowing method is universally superior. Studies such as those reported by Cuomo et al. (2001) and Schlueter and Tracy (2012) suggest that under certain conditions, including strong vegetation suppression or favourable slope position, broadcasting can perform comparably to drilling. Moreover, sowing success may depend more on microclimate, fertility management, and sward competition than the sowing method itself (Guretzky et al., 2004). From a systems perspective, we argue that the value of sowing strategies lies in their adaptability rather than their technical optimisation. In NZ diverse dairy and hill country landscapes, especially under shifting climate and labour constraints, establishing resilient pastures may require embracing a 'toolbox' of flexible sowing approaches, with each method matched to specific land units, enterprise types, and agroecological goals. For systems where mechanical inputs may be deliberately minimised, broadcasting and frost-seeding may have strategic value in enabling diversification and regeneration of marginal land without major soil disturbance. These methods may also support transitions away from high-input systems towards more 'regenerative models', particularly if coupled with innovations in seed coating, mixed species sowing, or seed placement via drones or autonomous spreaders.

4.3 Drilling and row spacing: Precision and persistence trade-offs

Seed-to-seed spatial relationships during pasture establishment, whether through grid sowing, single-pass row planting, or scatter techniques, can significantly affect stand uniformity, grazing behaviour, and soil health. Unfortunately, these planting/sowing patterns are often designed for monoculture optimisation and their effects on pasture diversity, resilience, and agroecosystem function remain relatively underexplored. Grid or matrix sowing, which involves perpendicular seeding passes, may enhance uniformity and reduce intra-species competition, theoretically supporting better root distribution and light capture. However, the additional equipment passes increase the risk of soil compaction, disrupt soil structure, and may introduce unnecessary cost and energy inputs, particularly on heavier soils or under wet conditions (Hamza and Anderson, 2005; Batey, 2009). In contrast, single-pass row sowing has been shown to provide comparable establishment success whilst reducing machine traffic, compaction, and energy use.

Row spacing also plays a crucial role in shaping pasture performance. Narrower spacing may promote faster canopy closure and greater weed suppression but can increase inter-plant competition for moisture and nutrients. In contrast, wider rows may improve airflow and rooting depth but leave soil exposed to weed pressure, potentially increasing reliance on herbicides, especially during early establishment phases. Innovations such as scatter plates or angled plates spread seeds within rows, aiming to balance intra-row density with inter-row space. However, these innovations bring their own trade-offs, including more bare soil exposure during early stages and higher variability in seedling emergence.

Whilst much of the literature on row spacing stems from row-crop systems, its relevance to diverse and mixed-species pasture systems is increasing. In that, variable row configurations could enable 'functional layering', with deeper-rooted species sown in wider rows and shallow-rooted groundcovers filling inter-row spaces, thereby supporting nutrient capture, grazing selectivity, and water-use efficiency. Alternatively, pasture species could be spatially separated into functional groups (grasses, legumes, and/or herbs), to enable selective/targeted applications of herbicides or fertilisers that meet specific group needs. Spatial diversification could also facilitate robotic management systems, allowing precision application of seed, inputs, or weed control with reduced 'collateral damage' to sward structure. Here, we argue that row spacing should not be treated as a fixed agronomic parameter, but as a design variable within a more holistic pasture system, one that considers not just establishment success but also long-term productivity, soil health, and adaptability. This is particularly relevant as NZ pastoral systems face growing pressure to reduce inputs, diversify species, and manage land with greater precision and resilience. Research is needed to test how sowing configurations interact with species mixes, plant persistence, soil types, and grazing pressures over time, and how these sowing/planting choices can be aligned with broader agroecological goals.

4.4 Sowing depth: Balancing precision with practicality

Sowing depth is a critical determinant of seedling emergence, however, it often remains underexplored in pasture system design. For common NZ pasture species including white clover and perennial ryegrass, optimal depths differ substantially, ranging from 5 to 10 mm for clover and up to 20 mm for perennial ryegrass (Bartholomew et al., 1981; Thom et al., 1985; Black et al., 2006). In mixed-sward systems, this discrepancy raises a persistent challenge, of how to sow multiple species with differing depth requirements without compromising establishment or increasing costs and soil disturbance. Recommendations in NZ often give a generalised sowing depth of 10–15 mm, which may favour one species at the expense of another, and may be especially so in pastures where shallow-germinating legumes are sown with deeper-rooted grasses or herbs/broadleaves. This highlights the need to rethink sowing as a layered, spatially sensitive process, which potentially requires adoption and adaptation of variable-depth seeding equipment. However, sowing species separately, though more precise, may involve additional machinery passes, compounding costs, time, and risks of compaction or erosion.

Seed weight and sowing depth are also tightly linked. In that, as sowing depth increases, the energy required for seedling emergence rises disproportionately for small-seeded species, which may reduce seedling emergence success (Porter et al., 1993). However, deeper sowing is not all negative and can improve overwinter survival and drought resilience by placing the seed (and subsequent germinated seedling) closer to more 'stable' soil moisture layers. This presents a common trade-off found in most sown agronomic crops, one where rapid emergence needs to be balanced against longer-term resilience, particularly under increasingly erratic climate conditions. Furthermore, soil compaction, whether caused by grazing livestock or heavy machinery, has a strong negative effect on seedling emergence, particularly for legumes such as white clover, and to varying degrees perennial ryegrass and lucerne (Campbell and Swain, 1973; Frost, 1988; Douglas and Crawford, 1991; Greenwood and McKenzie, 2001). High soil bulk density can inhibit root elongation, reduce oxygen diffusion, and delay or reduce germination. Importantly, the sensitivity to compaction differs among species and even among cultivars within species (Charles et al., 1991; Houlbrooke et al., 1997), reinforcing the need for specific species/cultivar and soil specific sowing strategies.

Looking forward, precision seeding technologies may offer solutions, which would allow species-specific depth control within the same pass or enabling spatial partitioning of pasture zones by depth and species function. However, these tools must be matched with practical farm realities, including terrain limitations, time constraints, and equipment costs. In the meantime, a greater understanding of species interactions under suboptimal sowing conditions is urgently needed, to guide decisions where 'precision' is not feasible. We propose that sowing depth should not be viewed merely as an 'agronomic fine-tuning' but as a critical interface between seed biology, soil condition, and farming system resilience. In mixed-species pastures, sowing depth decisions influence not only emergence but also the long-term functional balance of the sward, affecting rooting depth, nutrient cycling, and pasture persistence.

4.5 Seeding rates: Competition, establishment, and system resilience

Seeding rate is a fundamental 'lever' in pasture establishment, influencing not only initial germination success but also subsequent plant growth dynamics and species interactions. Whilst legumes generally exhibit higher germination rates compared to grasses, this does not always translate into vigorous early growth or competitive dominance (McWilliam et al., 1970). In mixed-species swards, careful calibration of seeding rates is essential to balance competitive interactions and allow slower-germinating species to establish (Culleton et al., 1986; Praat et al., 1996).

In NZ pastoral systems, recommended seeding rates for perennial ryegrass typically range from 20–25 kg ha^{-1} for diploid cultivars and 25–30 kg ha^{-1} for tetraploids (Campbell and Kunelius, 1984; Black et al., 2006). High perennial ryegrass seeding rates can increase early biomass production but may suppress legume establishment through competitive exclusion, reducing sward diversity and long-term system resilience (Gerard et al., 2009; Schlueter and Tracy, 2012; Hughes, 2017). Conversely, lowering perennial ryegrass seeding rates can encourage white clover and other less-aggressive species to establish and persist, promoting functional complementarity within the sward. Reduced seeding rates for perennial ryegrass may be offset by increased tillering and tiller survival, whilst maintaining pasture productivity and mitigating excessive competition (Hoen, 1968; Culleton et al., 1986; Praat et al., 1996). However, higher seeding densities often lead to increased intraspecific competition, which can exacerbate pasture vulnerability to abiotic stresses such as drought, nutrient limitation, and weed invasion.

Despite agronomic guidelines, practical seeding rates frequently exceed recommendations by up to 50%, driven in part by local experience, on-farm risk mitigation strategies, and climatic variability (Brock and Thomas, 1991). This practice reflects farmers' uncertainty around seedling survival and establishment success and also increases input costs which may lead to diminished returns if excessive competition limits pasture longevity. For example, in drought-prone or semi-arid environments, increasing seeding rates can be a pragmatic response to reduce the risk of poor establishment. However, this strategy entails trade-offs, including higher upfront seed costs and potentially greater resource competition post-establishment. Lower seeding rates combined with adjusted N inputs may offer a more sustainable pathway, especially where pasture production is managed below maximum yield thresholds.

We suggest that adaptive seeding strategies integrating real-time environmental monitoring, species/cultivar-specific growth traits, and soil conditions could optimise seeding rates, reducing waste and enhance sward resilience. Precision agriculture tools, including variable-rate seeders, could facilitate site-specific management, aligning establishment practices with evolving agroecological goals.

4.6 Mixed species swards and spatial separation: Diversity and functional complementarity

Mixed-species swards have gained increasing interest in NZ pastoral systems due to their potential to improve grazing productivity (Rochon et al., 2004; Sanderson, 2010), animal performance (Pembleton et al., 2015; Vasta et al., 2019; Refshauge et al., 2022), and ecosystem services, including N use efficiency and drought resilience (Finn et al., 2013). However, translating these 'theoretical' benefits into persistent and functional pasture systems remains a major challenge. Despite initial gains in biodiversity and forage quality, multispecies pastures often experience diversity loss over time, with dominant species, typically perennial ryegrass or white clover, eventually outcompeting other sown pasture species (Michalk et al., 2003; Skinner and Dell, 2016). This ecological convergence undermines the resilience and complementarity that diverse swards aim to promote.

Spatial separation during sowing could reduce early interspecific competition and may allow more niche differentiation and effective resource utilisation. Hayes et al. (2021), working in semi-arid Australia, demonstrated that alternate row sowing of lucerne and subterranean clover helped maintain species coexistence by separating root zones and light capture patterns. This technique could be adapted to NZ conditions using precision seed drills capable of row-specific seeding rates, species selection, and sowing depths. However, spatial separation is not a panacea and introduces its own trade-offs. For example, it may limit plant–plant interactions that confer mutual benefits such as N transfer or allelopathic suppression of weeds. Furthermore, the benefits of spatial separation are likely context-dependent, varying with soil type, rainfall patterns, pasture species traits, and grazing management.

We feel that long-term persistence of multispecies swards may depend less on sowing configuration per se and more on system-level interactions, including grazing intensity (or cutting regime), nutrient cycling, and pest pressure. Spatial separation may offer an initial advantage during establishment, but maintaining diversity will likely require adaptive management over the entire pasture lifecycle. This raises key questions around agroecological design: should we be designing pastures for spatial stability or for temporal succession, for hyper-diversity or functional diversity? What levels of species turnover are acceptable or even beneficial? How might spatial separation interact with rotational grazing, fertility gradients, or site-specific soil constraints?

We suggest that research and practice must shift from a one-size-fits-all prescription towards dynamic, site-tailored frameworks that integrate spatial and temporal diversity management. Technologies such as variable-depth drills and species-specific sowing modules currently offer promising tools, but they must be deployed within broader strategies that explicitly account for ecological and agronomic complexity. Ultimately, we suggest that rethinking pasture establishment as a process of 'ecological design', rather than a technical input, will be a key driver for maintaining functionally diverse swards in the face of growing environmental and economic pressures.

5 Germination and persistence

Seed germination and subsequent persistence vary markedly across pasture species, and are shaped by genetic traits (e.g., dormancy, seed size, coat thickness) and environmental conditions. Among the most influential drivers are soil temperature and moisture, which regulate both seed dormancy release and germination. For example, autumn-sown white clover germinates faster than perennial ryegrass, but its subsequent growth lags, with perennial ryegrass leaf appearance occurring up to three times faster (Brock and Hay, 2001). This 'temporal mismatch' highlights the need for 'tactical management' interventions, including early grazing during mid-winter, to reduce perennial ryegrass dominance and support clover establishment. A solid understanding of thermal time requirements (i.e., the temperature-development relationship) is essential for optimising sowing windows and matching compatible species. Species with slower development rates or smaller seed sizes, such as cocksfoot or tall fescue, typically benefit from spring sowing to maximise establishment opportunities (Moot et al., 2000). Seasonal conditions further influence outcomes, with autumn sowing generally favoured at drier sites and spring sowing at wetter locations, reinforcing the importance of aligning sowing strategy with moisture availability (Tozer et al., 2016; Tozer and Douglas, 2016).

Following germination, the capacity of seedlings to draw on endosperm reserves plays a critical role in their early vigour and competitive ability. Species like perennial ryegrass, with relatively large reserves, establish more readily, whilst others with limited reserves, including Timothy and tall fescue, may require careful post-sowing support in order to survive (Brock et al., 1982; Moot et al., 2000). Water availability is a key determinant of pasture persistence, particularly for drought-sensitive species such as perennial ryegrass and white clover. Avoiding grazing during water-deficit periods is essential to reduce stress and maintain stand longevity. Within species, small-leaf white clover cultivars exhibit greater drought resilience, attributed to denser canopies and reduced evapotranspiration (Brock and Kim, 1994). Broader trends in reduced persistence of temperate pasture species may also reflect increasing climatic variability and intensifying drought frequency under climate change.

We suggest that these insights underscore the need for renewed focus on species and cultivar selection based on drought tolerance and water-use efficiency. As NZ climate shifts, resilience traits may become as critical as yield potential in determining the long-term success of pasture systems. Adding to this complexity, there is a substantial within-species variability in response to both abiotic and biotic stressors (Thom et al., 2011; Chapman et al., 2017). Allelopathic interactions, such as those between perennial ryegrass and clover, may hinder establishment (Smith and Martin, 1994; Miller, 1996; Wardle et al., 1996), but positive interactions could also be harnessed. For example, chicory-lucerne mixtures have been shown to enhance N fixation and improve overall pasture performance (Gardner et al., 2023). Together, these factors point to more 'nuanced', climate-adapted, and species/cultivar-aware establishment strategies, particularly in multispecies swards, if pasture systems are to remain resilient and productive in a changing environment.

5.1 Self-thinning and early-stage competition: An agroecological approach

Seedling dynamics during pasture establishment are often framed in terms of emergence percentages and early vigour. However, ecological processes such as self-thinning introduce complex interactions that are frequently underappreciated in conventional pasture sowing strategies. Some species exhibit enhanced germination when sown at higher densities, a phenomenon attributed to favourable microsite moisture conditions or the release of germination-promoting compounds from seeds (Linhart, 1976; Waite and Hutchings, 1978), suggesting that higher seeding densities may confer resilience in unpredictable conditions (Skinner, 2005). However, this strategy carries inherent trade-offs; whilst dense sowing may boost initial emergence, it can also trigger intense intraspecific competition among seedlings, leading to rapid self-thinning as they vie for limited light, water, and nutrients (Ross and Harper, 1972).

In multispecies pasture systems, these dynamics become even more complex. Different species exhibit divergent root-to-shoot allocation strategies, emergence timing, and seed mass (Wilson, 1988), all of which mediate competitive outcomes. Larger-seeded species may dominate initial growth stages but may not persist if their root systems are poorly matched to prevailing soil or climatic conditions. Conversely, small-seeded, slower-establishing species may be suppressed before they can establish and contribute to the sward's productivity. In addition, interactions between seed traits and micro-environmental variability, such as localised differences in soil moisture, compaction, fertility, and microbial communities, may be amplified by within-field heterogeneity. This heterogeneity influences not just establishment success, but also long-term sward composition, functional diversity, and resilience.

We suggest that the ecological implications of self-thinning extend beyond mere seedling survival. High-density sowing followed by seedling mortality can reduce establishment efficiency, increase seed costs, and skew species composition, negatively impacting long-term pasture performance, resilience, and ecosystem services. However, few pasture establishment guidelines explicitly address these dynamics, often promoting blanket seeding rates that do not account for species/cultivar-specific or site-specific trade-offs. From a systems perspective, managing for self-thinning means moving beyond 'how much seed should we sow' towards asking how density-dependent interactions shape long-term pasture composition, performance, resilience, and agroecosystem function. We suggest that we may unintentionally be selecting for 'aggressive' early competitors at the expense of functional diversity, and we question how sowing methods and patterns influence root system development, water use efficiency, and resilience to climate variability. We argue that a more 'nuanced' understanding of self-thinning in pasture systems could help inform seed mixture composition and sowing density decisions. Expectations of sward performance over time, particularly in diverse and multifunctional dairy pasture swards, would benefit as key components of sustainable and resilient agroecosystems. Future approaches should integrate ecological theory with empirical agronomic knowledge and thereby optimise early competition dynamics, and not only focus on maximisation of short-term biomass, but rather seek resilient and functional diversity from renewed pasture swards.

6 Post-sowing management: Pasture species composition and trade-offs

Post-sowing management is often framed as a technical exercise, where optimising defoliation frequency, protecting seedlings, and managing competition is critical. However, when viewed through an agroecological lens, it is a critical period of ecosystem assembly, where timely decisions about grazing, density and disturbance drive long-term trajectories of species persistence, functional diversity, and soil resilience. As seeds germinate and grow, they enter a competitive environment for resources, both within and between species. Ross and Harper (1972) reported that seedlings often grow into less crowded areas between rows, reflecting a behaviour of avoidance or resource exploitation rather than aggressive competition. In contrast, Donald (1951) proposed that higher plant densities may be needed to fully utilize available resources under ideal conditions. This apparent contradiction illustrates a core tension, where the optimal establishment density for a pasture species is not fixed, but depends on interactions between a variety of drivers, including species traits, topography, soil, and climatic conditions. Furthermore, whilst oversowing may accelerate early canopy cover, it can also intensify competition, by limiting rooting depth and hence access to available resources, and thereby increase vulnerability to climatic stress (e.g., later drought events).

Following pasture renewal, the timing of grazing events can represent a major post-sowing disturbance in NZ dairy systems. Whilst moderate grazing can stimulate compensatory regrowth and manage competitive balance, excessive frequency or intensity, especially in the establishment year, can severely limit root biomass, reduce energy reserves that include carbohydrates and nitrogenous compounds, and weaken plant resilience (Detling et al., 1979; Schuman et al., 1999). Perennial ryegrass, particularly when sown at high densities, are especially vulnerable to this stress. However, the degree of 'damage' is not universal and varies with timing, rest periods, soil condition, defoliation intensity, residual height, and species/cultivar-specific responses (Holland and Detling, 1990). We feel that this variability challenges the 'one-size-fits-all' approach to pasture management. For example, rotational grazing is often promoted as a regenerative solution, and has been shown to support white clover biomass under drought (Brink and Pederson, 1993) and outperform other grazing methods for hay production in cool, subhumid environments (Oates et al., 2011). However, rotational systems can also lead to significant stolon loss during summer dry periods (Sanderson et al., 2003) and may not adequately protect vulnerable species if rest periods are too short or livestock pressure is too high. Similarly, frequent defoliation has been reported to reduce tillering in perennial ryegrass but enhance clover branching (Wen and Jiang, 2005), suggesting that pasture performance outcomes hinge on species/cultivar interactions, not just individual plant responses. We feel that these findings highlight the importance of post-sowing management and the need to balance ecological trade-offs with production goals and needs. We suggest that there is no single best management practice; the right decision depends on various interconnected factors, including soil structure, climate patterns, farmer objectives, and the ecological goals of the system. For example, protecting white clover may require limiting early grazing, but doing so might delay perennial ryegrass tillering or reduce overall early forage availability, whilst treading damage may further complicates the picture, as trampling can disrupt seedling emergence, compact soils, and shift botanical composition (Brown and Evans, 1973). The severity of these effects varies widely by livestock type, soil moisture, and sward structure, and again highlights the need for site-specific management rather than generalised rules. Therefore, to successfully balance these outcomes, we suggest a move beyond prescriptive management recipes, towards contextual, adaptive, and systems-informed approaches, which will require access to real-time scalable data.

We suggest that what is urgently needed is a systems-based evaluation framework that reframes post-sowing management, not as a discrete phase, but as an active component of long-term agroecosystem design. This would mean integrating basic ecological indicators, such as root-to-shoot ratios, species resilience, and soil structure into pasture management decisions. It would also require a more robust acknowledgement of uncertainty and variability, which is highly difficult, and would require the incorporation of 'feedback loops' into pasture management decision making that allows for 'correction' as conditions/seasons evolve. We feel that post-sowing management is a crucial site for 'ecological negotiation', where choices about grazing intensity, rotation/frequency, and residual are more than drivers of short-term productivity goals. For example, grazing intensity, rotation/frequency, and residual height shape root architecture, species balance, and the capacity of the system to withstand future stress. As climate pressures mount and the call for regenerative systems grows louder, pasture establishment must evolve from a one-off technical task into a more strategic phase of agroecosystem management.

6.1 Irrigation and drainage: A strategic input in a water constrained future

Irrigation is often viewed as a 'tactical solution' to water deficits during pasture establishment, however, in the context of increasing climate variability and rising intersectoral competition for water, we suggest that it should be reimagined as a 'strategic pasture input' for sustainable production from a resilient agroecosystem. In that, the role of irrigation is not merely to ensure establishment, but to mediate ecological thresholds for plant survival, competition, and long-term resilience, where the effectiveness and sustainability of irrigation and drainage projects depend not only on timing, and volume, but also on species-specific water requirements, the quality of the water, precipitation events, and the capacity of the soil to retain and transmit moisture. For example, cool-season grasses may respond well to shallow, frequent irrigation, whilst warm-season or deep-rooted species may require less frequent, deeper watering to align with their root architecture and phenological rhythms. Tailoring irrigation to soil type (and drainage requirements) and functional plant traits and phenology, would promote an 'ecologically informed' water use and could reduce overreliance on irrigation as a default establishment tool. However, the availability, quality, and regulatory governance of irrigation water resources are becoming increasingly complex in NZ. Agricultural access to water now competes directly with municipal, industrial, and environmental allocations, particularly in regions where freshwater resources are already over-allocated or degraded. Poor-quality water, such as sources high in salinity or agricultural runoff, may further constrain species choice or compromise long-term soil structure and soil health. Going forward, we suggest an integrated water governance approach to pasture irrigation, one that acknowledges agroecosystems not as isolated production units but as part of a broader 'socio-hydrological' system, with multiple competing, yet interlinked, demands on the hydrologic continuum.

We argue that from an ecological standpoint, irrigation should not be used to compensate for poor pasture-environment matching. Instead, it should serve as a 'bridging input' to support species establishment only where long-term rainfall trends or soil water retention capacities align with pasture persistence. Otherwise, short-term establishment gains may lead to long-term dependency or degradation of surface and groundwater resources, particularly under increasing climate variability or if water-intensive species are introduced in marginal or drought-prone regions in NZ. We suggest a 'future-fit' approach to irrigation in pasture systems in NZ, which would involve a critical trade-off assessment that is not solely agronomic, but rather based on a series of system-level questions/considerations that intersect with climate adaptation, biodiversity, and landscape-scale water stewardship; for example, which pasture species justify the use of limited water resources? Can establishment windows be shifted to reduce water stress? Do diverse pasture species mixes support mutual water-use efficiency and/or hydraulic lift? We suggest that irrigation, whilst offering critical advantages during pasture establishment, needs to be embedded within a broader framework that values resilience over short-term productivity. Therefore, going forward, we suggest that irrigation use in NZ pasture systems is best viewed not as a guarantee, but rather as an 'ecological lever', which should be used selectively and with care, and aligned with long-term sustainability goals, climate forecasts/projections, and equitable water governance.

7 Limitations of current approaches: Rethinking pasture establishment

Conventional approaches to pasture establishment and renewal in NZ pastoral systems often emphasise short-term performance and simplicity of execution, which typically include full cultivation and chemical termination followed by re-sowing. Whilst these methods can effectively reset sward composition and address severe pasture decline, they involve significant economic, ecological, and operational trade-offs, for which we feel a systems-level re-evaluation is warranted.

From an economic standpoint, pasture renewal is typically framed as a cost–benefit calculation, where the upfront investment in seed, labour, and machinery must be justified by future gains in pasture productivity and quality. However, we believe that this framing oversimplifies the decision-making context. Hopkins et al. (1990) argued that the yield benefits of pasture renewal may be considerably diminished once the 'establishment lag' and associated production losses are accounted for. Carswell et al. (2019) reported that although newly sown pastures often show superior productivity in their first year, this 'advantage' may not persist over time, which raises questions about return on investment beyond the initial establishment phase, and challenges the assumption that pasture renewal is always a net economic positive. Even when successful in the short term, renewed pastures may underperform over time due to poor persistence, pest damage, nutrient imbalances, poor grazing management, and climatic stress (Bastiman and Mudd, 1971; Bellotti and Blair, 1989a; Scott et al., 2000).

We also argue that the risk of failure in pasture renewal is not negligible, and yet, the causes of establishment failure remain under-researched. Whilst agronomic guides often recommend pasture renewal as a standard corrective measure, there is limited information on frequency and triggers of reseeding efforts, particularly when viewed under real-world conditions. Furthermore, economic thresholds for 'success' vary substantially across production systems. On high-input, high-output dairy farms with access to irrigation, nutrient inputs, and mechanised reseeding, the costs of renewed pastures may be recouped quickly due to their direct influence on improved milk yield and quality. In contrast, lower-input systems such as dryland sheep and/or beef farms, which in NZ are often located on more topographically constrained land, may struggle to justify renewal on either economic or logistical grounds. These site-specific realities reinforce that no single approach can be optimal at all times or across all systems and scales. Beyond economics, current approaches often externalise environmental and system-level costs. For example, cultivation-based renewal may degrade soil structure, reduce microbial activity, and increase GHG emissions, whilst chemical termination of swards, particularly with glyphosate, raise concerns around residues, herbicide resistance, and impacts on non-target organisms.

Whilst we acknowledge that when pasture renewal is well-timed, targeted, and supported by good management, it can be economically viable and environmentally beneficial (Rapiya et al., 2025). However, over time, poor management and ill-conceived and repeated pasture renewal cycles may lead to 'system fatigue' and loss of resilience (e.g., increased weed and pest pressure, and reduced ecosystem service provisions), and this makes renewal an inevitable cyclic event, with diminishing returns. However, the risks of failure are rarely accounted for in economic decision tools or extension recommendations for pasture renewal. We argue that the core issue is not whether pasture renewal can work, but rather when, where, and under what system constraints and goals it makes sense. Trade-offs are inevitable, for example, between short-term yield and long-term persistence, between simplicity and ecological disruption, between immediate economic return and broader agroecosystem stability. These trade-offs are often under-acknowledged in both research and advisory literature, which we feel leads to implicit assumption that renewal is always successful, and more renewal is inherently better.

We believe that what is needed is not a 'binary evaluation' of pastures, i.e., "to renew or not to renew," but rather we advocate for the development of a systems-based evaluation framework, that considers pasture renewal as a management option nested within a broader agroecological and socio-economic context. For example, this would include asking: how does renewal affect nutrient cycling? What does it mean for biodiversity and soil function? What role does it play in whole-farm resilience, climate adaptation, and GHG emissions mitigation? And ultimately, how does it align with the farmer's long-term goals? We suggest reframing pasture renewal from a routine agronomic intervention to a strategic, context-dependent decision, best assessed through integrated models that combine ecological, economic, and social indicators. Only then can pasture renewal be used not just to 'fix' pastures, but also to optimise sustainability and resilience, along with economic returns.

7.1 Pasture diversity and function: Role of stochasticity in pasture establishment

Traditional pasture management has often viewed persistence as the 'capacity' of specific sown species to maintain 'dominance' overtime. However, emerging ecological perspectives suggest that resilience in diverse pastures may not depend on maintaining 'fixed species' identities, but rather on functional stability through compositional change (Orwin et al., 2022). From this perspective, species turnover and stochastic establishment dynamics can be viewed not as 'management failures' but as ecological adaptation to variable climates, soils, and grazing pressures.

Embracing this stochasticity requires a shift in management goals and a move from maintaining static assemblages towards 'self-organising' systems that express adaptive responses. Such systems rely on 'functional redundancy', diverse phenological strategies, and belowground trait variability that collectively sustain productivity and nutrient cycling even as species composition fluctuates. We suggest that pasture establishment strategies would therefore benefit from encouraging functional diversity and ecological plasticity, rather than attempting to tightly control post-sowing trajectories. This approach aligns with agroecological principles, where disturbance, recovery, and successional processes are recognised as essential drivers of system renewal. We argue for a 'revaluation' of pasture diversity, where 'functional' rather than 'taxonomic' persistence is prized, thereby providing greater on-farm flexibility to environmental change. We suggest that ecological stochasticity could be integrated as both an 'uncertainty' and an 'opportunity' within pasture management, where renewal trigger points, including declining pasture cover, legume loss, or increased weed ingress, could be reinterpreted not as rigid thresholds for pasture renewal, but as signals of functional imbalance, which would require an 'ecological correction' rather than full re-sowing. For example, instead of reinstating an 'identical' species mix, farmers could focus on re-establishing functional groups (grass, legume, or forbs/herbs) critical to soil fertility or water capture (e.g., deep-rooted forbs/herbs or N-fixing legumes). Monitoring tools such as normalized difference vegetation index (NDVI), spectral diversity indices, and soil respiration assays could track functional performance rather than uniformity of species composition. This feedback-based management strategy recognises variation, turnover, and adaptive reassembly as integral components of pasture resilience and sustainability. By reframing pasture persistence through the lens of system function, we move on-farm decision making from reactive and control-orientated cues to a more adaptive and considered response. This approach situates pasture establishment within a broader agroecological continuum, linking renewal, persistence, and productivity as interdependent processes within dynamic, self-regulating systems.

8 New and emerging technologies: Production and ecological innovation

New and emerging technologies are a rapidly expanding area in agriculture and offer powerful tools for transforming pasture establishment in NZ pastoral systems. For example, precision planting equipment, autonomous machinery, virtual fencing, and smart irrigation all improve efficiency and precision (Bechar and Vigneault, 2016; Duckett et al., 2018; Lomax et al., 2019; Shafi et al., 2019; Verdon et al., 2021), whilst potentially offering opportunities for enhanced sustainability. However, we feel that whilst these innovations carry the potential to reshape pasture-based systems, they must be evaluated not only for their technical performance, but also for how they interact and fit into current farm systems, and what they mean for long-term resilience and sustainability. For example, precision agriculture tools, including GPS-guided seed drills, sensor-integrated machinery, and satellite imagery, enable targeted interventions based on variability of soil fertility, moisture, and topography. This spatial sensitivity could reduce input use, improve establishment rates, and tailor sowing to soil condition, seed type, and microclimates (Sishodia et al., 2020). Similarly, virtual fencing could allow for adaptive grazing management, which could minimise overgrazing, protect vulnerable seedlings, and maintain botanical diversity. These tools support more flexible and ecologically responsive management, which we argue is essential in pasture systems where plant and sward dynamics are highly context-dependent.

Technologies that enhance plant performance, including improved seed genetics, microbial inoculants, and drought or heat-tolerant cultivars, also contribute to agroecological resilience (Santos et al., 2019; Caradus et al., 2021). However, the promise of such innovations must be critically examined against their long-term sustained compatibility with soil biology, local agroecosystem functions, and farmer knowledge. For example, soil health tools and regenerative agriculture practices (Kibblewhite et al., 2008; Teague and Kreuter, 2020) are gaining traction, but their effectiveness depends on context-specific factors like stocking rate, species mix, and grazing regime within a particular farm setting and climate.

Critically, we feel that the biggest hurdles slowing introduction of new technologies on farm, are the 'new' trade-offs that they represent and the speed at which these decisions need to be made. For example, high up-front costs, uncertain return on investment timelines, and the need for specialised skills often restrict adoption, especially for small and medium-sized operations. Technologies that increase operational complexity, require high data literacy, and are perceived as 'solutions looking for problems' or 'expensive paperweights' may face resistance and fail to deliver sustained benefits (Giller et al., 2021). Moreover, ecological benefits, including improved soil structure and microbial diversity, may take years to manifest and may be difficult to quantify and attribute directly to any single input or tool.

We believe this highlights a broader challenge: on-farm technologies cannot be evaluated in isolation. Their impact depends on how well they integrate into a farm's existing ecological, economic, and social context. A drone or smart irrigation system might improve short-term pasture performance, but if it increases dependence on external inputs, undermines soil health, or narrows farmer autonomy, it may be misaligned with long-term farm sustainability and resilience goals. Equally, tools that enhance decision-making, including machine learning and artificial intelligence (AI), that predict pasture growth or animal performance, must be transparent, accessible, and aligned with farmer experience, not just be optimised for 'abstract off-farm metrics'. These tensions highlight the need for systems-based evaluation frameworks that place innovation within the broader goals of agroecological resilience and sustainability, and farm capacity, for informed decision making. We suggest that instead of asking whether a technology works, we should ask for whom it works, when it works, and at what environmental, societal, and economic cost. We argue that to realise the full potential of current and emerging technologies in pasture establishment, we must shift from a paradigm of 'technology-based fixes' and focus more on

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TABLE 1 Summary of key synergies and trade-offs for pasture establishment and management in Aotearoa New Zealand dairy systems.

Factor	Synergies	Trade-offs	Effect on pasture establishment
Seed Germination & Species Selection	- Enhanced germination with higher sowing rates due to moisture retention and chemical triggers (Linhart, 1976; Waite and Hutchings, 1978). - Early emerging seedlings gain competitive advantage (Ross and Harper, 1972).	- Variability in soil and seed size can affect germination rates unevenly. - Complex interactions in mixed swards (Wilson, 1988).	- Improved initial establishment with optimised conditions. - Potential for uneven establishment due to variability.
Sowing Techniques	- Precision in sowing depth, rate, and timing enhances seed-soil contact and establishment (Taylor et al., 1972; Campbell, 1985). - Adaptability of methods like frost-seeding supports diverse conditions (Casler et al., 1999).	- Broadcast seeding offers flexibility but lower, variable emergence due to environmental stress (Taylor et al., 1969). - Direct drilling limited by terrain and compaction risks (Morris et al., 2010).	- Enhanced establishment with precise techniques; adaptability improves resilience in marginal lands. - Trade-off between cost, precision, and labour in method selection.
Pre-Sowing Management	- Chemical termination reduces soil disturbance and C/N losses on erosion-prone soils (Aslam et al., 2000). - Cultivation provides a clean seedbed for early establishment (Bellotti and Blair, 1989b).	- Chemical use raises concerns over residues, biodiversity loss, and P leaching (Arias-Estévez et al., 2008; Rose et al., 2018). - Cultivation degrades soil structure and increases erosion risk.	- Faster establishment with chemicals but long-term soil health concerns. - Better long-term soil health with cultivation, potentially offsetting short-term establishment gains.
Post-Sowing Management	- Rotational grazing supports white clover biomass and root health with rest periods (Holland and Detling, 1990; Brink and Pederson, 1993). - Frequent defoliation enhances clover branching (Wen and Jiang, 2005).	- Overgrazing in Year 1 limits root biomass and resilience (Thom et al., 2011). - Rotational systems risk stolon loss in drought (Sanderson et al., 2003). - Treading damage disrupts growth (Brown and Evans, 1973).	- Promotes species diversity and resilience with adaptive management. - Risk of degradation if mismanaged, affecting long-term pasture health.
Economic Considerations	- Potential for yield benefits over time with adaptive practices (Hopkins et al., 1990). - High-input systems may break even faster with irrigation and mechanisation.	- High upfront costs and establishment lag diminish short-term returns (Carswell et al., 2019). - Lower-input systems struggle with economic justification on constrained land.	- Long-term economic benefits through improved pasture productivity. - Initial investment and site-specific viability affect adoption and short-term financial outcomes.
Environmental Impact	- Regenerative practices enhance soil health and ecosystem services (Teague and Kreuter, 2020). - Terminated residues may buffer erosion (McNally et al., 2017).	- Cultivation and herbicides degrade soil structure and increase GHG emissions (Paustian et al., 2000). - N losses from termination amplify in wet conditions (Belyaeva et al., 2016).	- Positive long-term impact on sustainability with regenerative methods. - Short-term negative environmental effects from conventional practices on soil and water quality.
New Technologies	- Precision agriculture can optimise resource use and reduce inputs (Shafi et al., 2019). - Improved seed genetics enhance resilience (Caradus et al., 2021). - Virtual fencing supports adaptive grazing (Lomax et al., 2019).	- High initial costs and training needs limit adoption (Giller et al., 2021). - Complexity and delayed ecological benefits challenge integration (Kibblewhite et al., 2008).	- Potential for dramatic improvement in establishment efficiency and sustainability. - Adoption hindered by cost, complexity, and integration issues, affecting the rate of implementation.
Challenges & Gaps	- Awareness of long-term study needs drives future research (Fraser et al., 2014). - Varying definitions of success highlight research gaps (Thom et al., 2011; Tozer et al., 2016).	- Lack of long-term, system-level data on persistence and economic viability (Cartmill and Donaghy, 2024). - Disconnect between research and farmer priorities (Bellotti and Blair, 1987).	- Identifies areas for research refinement - Current knowledge gaps limit effectiveness of establishment strategies.
Future Research Needs	- Comparative studies across conditions to clarify best practices (Cartmill and Donaghy, 2024). - Technology adoption research to address barriers (Giller et al., 2021).	- Requires significant research investment with delayed practical outcomes. - Complexity of integrating ecological and economic factors.	- Enhances understanding and optimization of establishment. - Time and resources needed may delay practical advancements in management strategies.

The final five rows (Economic Considerations, Environmental Impact, New Technologies, Challenges & Gaps, and Future Research Needs) are presented as system-level factors influencing pasture establishment rather than as collateral dimensions. This structure maintains a consistent cause/effect logic (Factor - Synergies - Trade-offs - Effect) and reflects how these drivers operate within an integrated farm system.

adaptive technology which blends in farmer intuition with ecological knowledge, and plant-based adaptation and good agronomic practices. We suggest that this participatory technological innovation approach would enhance and support on-farm ecological decision making and promote the development of productive and adaptive pasture systems within the broader context of resilient and sustainable agroecosystems.

9 Conclusion

This perspective paper highlights the complexity and evolving nature of pasture establishment in NZ pastoral systems. The decisions surrounding establishment methods, ranging from cultivation and chemical termination to no-till and under-sowing, entail nuanced synergies and trade-offs (Table 1). Whilst conventional approaches have underpinned pasture productivity for decades, they increasingly raise concerns around long-term soil health, environmental sustainability, and resilience to climate variability. Whilst the use of mixed-species swards offers significant ecological and production benefits, including enhanced soil structure, greater drought tolerance, and improved animal nutrition, these systems demand sophisticated management to maintain botanical diversity and functional balance, particularly under intensive grazing. Likewise, precision in sowing - considering depth, rate, and timing - is critical, especially due to species/cultivar-specific sensitivities that influence early establishment and competitive dynamics. Post-establishment grazing management is equally crucial. For example, rotational systems with strategic rest periods can improve root architecture and pasture persistence, particularly for vulnerable but valuable species like white clover. However, these benefits are contingent on adaptive management and close observation, which will require a revaluation of the quality of technical support available and on-farm experience/knowledge.

This perspective paper also identified critical research gaps, particularly around the scarcity of long-term, system-level comparisons of establishment methods across diverse soil types, climates, and farm systems. We argue that without these studies, our understanding of pasture persistence, economic return, and resilience remains fragmented at best. Technological innovations, including sensors, robotics, and AI-driven decision support tools, could substantially improve establishment outcomes. However, on-farm adoption of technology remains limited due to high initial costs, training demands, and uncertainty over their performance under 'real-world/on-farm' conditions. Going forward, we call for a strategic research agenda, one that blends agronomic rigour, co-designed with farmer-led innovation, which explicitly considers the economic, environmental, and cultural dimensions of pasture renewal. Supporting this transition will also require investment in farmer education, cross-sector collaboration, and policy frameworks that reward sustainable land use. Only by addressing these challenges in an integrated way can NZ pasture-based systems remain productive, resilient, and environmentally responsible.

9.1 Future direction

Pasture establishment in NZ pastoral systems sits at the intersection of agricultural productivity, environmental stewardship, and socio-economic resilience. We suggest that advancing pasture establishment in NZ pastoral systems will require a shift from narrowly optimised productivity towards holistic system performance. This transformation depends on research innovation, collaborative knowledge exchange, and supportive policy environments that empower farmers to manage for resilience, regeneration, and long-term viability. Moving forward, we offer five strategic priorities (Table 2), which we believe must be addressed to future-proof NZ pasture systems under increasing climate, regulatory, and market pressures.

TABLE 2 Strategic priorities for a future-proof Aotearoa New Zealand dairy pasture systems.

Strategic priority	Description
Long-term, systems-based research	- Research should prioritise multi-year, regionally distributed studies that compare pasture establishment methods under varying soil, climatic, and management conditions, with focus on the ecological trade-offs of establishment method, persistence and profitability of mixed-species swards, and how establishment techniques influence soil health, carbon dynamics, nutrient retention, and biodiversity over time.
Integration of technology & decision support	- Research should focus not just on technical performance of new technology, but also on cost-effectiveness, scalability, and farmer usability and integration potential. Ensuring these innovations align with farmer decision-making processes and constraints will be crucial for widespread adoption.
Co-development with farmers & Māori landholders	- To be effective, future pasture systems must be co-designed with the communities who manage them. This includes meaningful engagement with Māori landowners and incorporation of mātauranga Māori alongside Western science to create culturally appropriate and ecologically grounded approaches. Participatory research models that build local capability and reflect diverse values will be essential.
Education, extension, & workforce development	- - The adoption of improved pasture establishment practices depends on access to high-quality training and advisory support. Future efforts should invest in extension frameworks that promote farmer-farmer learning, adaptive management, and system thinking. Equipping the next generation of farmers and rural professional with the interdisciplinary skills which span agronomy, ecology, data analytics, and cultural literacy will be fundamental.
Policy & incentive alignment	- Establishment practices must increasingly align with governmental climate and freshwater goals. Future policy settings should reward low-emissions, soil-conserving, and biodiversity-enhancing practices through incentive schemes, targeted subsidies, and/or market access advantages. Contentiously, regulatory frameworks must also enable farmer driven experimentation and adaptive management trials, with some oversight, but without penalty for early adopters.

Across the NZ dairy sector, a growing number of farmers are already applying agroecological principles through regenerative agriculture practices. These farmer-led initiatives often emphasise diverse pasture composition, adaptive grazing, and soil health restoration, which aligns with the systems-based ecological framework advocated here. Many regenerative practitioners are experimenting with deferred or rotational grazing to promote tillering, seed set, and deeper rooting, which effectively support self-reseeding and persistence without full pasture renewal cycles. We suggest that adoption of these practices reflect an emergent 'ecological literacy' within farming systems, where observation and responsiveness to plant–soil feedback are central to pasture and livestock management. Our perspective builds on, rather than replaces, these efforts by proposing a structured ecological decision framework that integrates farmer knowledge with quantifiable indicators and system feedback. Whilst regenerative practitioners often operate through experiential learning and observation, we argue for a framework which seeks to formalise these principles into decision-support systems that can link on-farm ecological data (e.g., soil respiration, ground cover, NDVI, etc.) with management 'triggers' for grazing, irrigation, or renewal. In this way, we bridge practical ecological management with science-based system diagnostics, creating a common platform for both innovation and monitoring. This highlights an important opportunity, to further integrate regenerative practices with more formal research programs, thereby enabling 'co-design' of adaptive management tools and metrics that reflect both farmer experience and ecological process understanding.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AC: Writing – original draft, Writing – review & editing, Conceptualization. MR: Visualization, Writing – review & editing, Conceptualization. DC: Writing – review & editing. DD: Writing – review & editing, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Afzal, I., Javed, T., Amirkhani, M., and Taylor, A. G. (2020). Modern seed technology: seed coating delivery systems for enhancing seed and crop performance. *Agriculture* 10:526. doi: 10.3390/agriculture10110526

Allen, V. G., Batello, C., Berretta, E., Hodgson, J., Kothmann, M., Li, X., et al. (2011). An international terminology for grazing lands and grazing animals. *Grass Forage Sci.* 66:2. doi: 10.1111/j.1365-2494.2010.00780.x

Al-Marashdeh, O., Cameron, K., Hodge, S., Gregorini, P., and Edwards, G. (2021). Integrating plantain (*Plantago lanceolata* L.) and Italian ryegrass (*Lolium multiflorum* lam.) into New Zealand grazing dairy system: the effect on farm productivity, profitability, and nitrogen losses. *Animals* 11:376. doi: 10.3390/ani11020376

Arias-Estévez, M., López-Periago, E., Martínez-Carballo, E., Simal-Gándara, J., Mejuto, J.-C., and García-Río, L. (2008). The mobility and degradation of pesticides in soils and the pollution of groundwater resources. *Agric. Ecosyst. Environ.* 123, 247–260. doi: 10.1016/j.agee.2007.07.011

Aslam, T., Choudhary, M., and Saggar, S. (2000). Influence of land-use management on CO2 emissions from a silt loam soil in New Zealand. *Agric. Ecosyst. Environ.* 77, 257–262. doi: 10.1016/S0167-8809(99)00102-4

Baars, J., and Cranston, A. (1977). Performance of'grasslands Matua'prairie grass under close mowing in the central North Island. *Proceedings of the New Zealand Grassland Association*, 139–147.

Baker, J. M., Ochsner, T. E., Venterea, R. T., and Griffis, T. J. (2007). Tillage and soil carbon sequestration—what do we really know? *Agric. Ecosyst. Environ.* 118, 1–5. doi: 10.1016/j.agee.2006.05.014

Bartholomew, P. W. (2005). Comparison of conventional and minimal tillage for low-input pasture improvement. *Forage Grazinglands* 3, 1–14. doi: 10.1094/FG-2005-0913-01-RV

Bartholomew, P., Easson, D., and Chestnutt, D. (1981). A comparison of methods of establishing perennial and Italian ryegrasses. *Grass Forage Sci.* 36, 75–80. doi: 10.1111/j.1365-2494.1981.tb01542.x

Bastiman, B., and Mudd, C. (1971). A farm scale comparison of permanent and temporary grass. *Exp. Husb.* 20, 73–83.

Batey, T. (2009). Soil compaction and soil management–a review. *Soil Use Manag.* 25, 335–345. doi: 10.1111/j.1475-2743.2009.00236.x

Bechar, A., and Vigneault, C. (2016). Agricultural robots for field operations: concepts and components. *Biosyst. Eng.* 149, 94–111. doi: 10.1016/j.biosystemseng.2016.06.014

Bell, N., Townsend, R., Popay, A., Mercer, C., and Jackson, T. (2011). Black beetle: lessons from the past and options for the future. *NZGA Res. Pract. Ser.* 15, 119–124. doi: 10.33584/rps.15.2011.3193

Bellotti, W., and Blair, G. (1987). "Use of sequential measurements of seedling density and seedling size distribution in the evaluation of sowing methods for perennial grasses" in Temperate pastures: Their production, use and management. eds. J. L. wheeler, C. J. Pearson and G. E. Roberts. Australia: Australian Wool, CSIRO.

Bellotti, W. D., and Blair, G. J. (1989a). The influence of sowing method on perennial grass establishment. III. Survival and growth of emerged seedlings. *Aust. J. Agric. Res.* 40, 323–331. doi: 10.1071/AR9890323

Bellotti, W. D., and Blair, G. J. (1989b). The influence of sowing method on perennial grass establishment. I. Dry matter yield and botanical composition. *Aust. J. Agric. Res.* 40, 301–311. doi: 10.1071/AR9890301

Belyaeva, O. N., Officer, S. J., Armstrong, R. D., Harris, R. H., Wallace, A., Partington, D. L., et al. (2016). Use of the agricultural practice of pasture termination in reducing soil N2O emissions in high-rainfall cropping systems of South-Eastern Australia. *Soil Res.* 54, 585–597. doi: 10.1071/SR15307

Berto, B., Ritchie, A. L., and Erickson, T. E. (2021). Seed-enhancement combinations improve germination and handling in two dominant native grass species. *Restor. Ecol.* 29:e13275. doi: 10.1111/rec.13275

Black, A., Moot, D., and Lucas, R. (2006). Spring and autumn establishment of Caucasian and white clovers with different sowing rates of perennial ryegrass. *Grass Forage Sci.* 61, 430–441. doi: 10.1111/j.1365-2494.2006.00552.x

Brink, G., and Pederson, G. (1993). White clover response to grazing method. *Agron. J.* 85, 791–794. doi: 10.2134/agronj1993.00021962008500040003x

Brock, J., Anderson, L., and Lancashire, J. (1982). Grasslands Roa'tall fescue: seedling growth and establishment. *N. Z. J. Exp. Agric.* 10, 285–289. doi: 10.1080/03015521.1982.10427884

Brock, J., and Hay, M. (2001). White clover performance in sown pastures: a biological/ecological perspective. *Proc. N. Z. Grassl. Assoc.* 63, 73–83. doi: 10.33584/jnzg.2001.63.2434

Brock, J., and Kim, M. C. (1994). Influence of the stolonkoil surface interface and plant morphology on the survival of white clover during severe drought. *Proc. N. Z. Grassl. Assoc.* 56, 187–191. doi: 10.33584/jnzg.1994.56.2102

Brock, J., and Thomas, V. (1991). The pasture ryegrass plant, what is it? *Proc. N. Z. Grassl. Assoc.* 53, 111–116. doi: 10.33584/jnzg.1991.53.2018

Brougham, R. (1959). The effects of frequency and intensity of grazing on the productivity of a pasture of short-rotation ryegrass and red and white clover. *N. Z. J. Agric. Res.* 2, 1232–1248. doi: 10.1080/11758775.1959.12289006

Brown, K., and Evans, P. (1973). Animal treading a review of the work of the late DB Edmond. *N. Z. J. Exp. Agric.* 1, 217–226. doi: 10.1080/03015521.1973.10427646

Byers, R., and Templeton, W. Jr. (1988). Effects of sowing date, placement of seed, vegetation suppression, slugs, and insects upon establishment of no-till alfalfa in orchardgrass sod. *Grass Forage Sci.* 43, 279–289. doi: 10.1111/j.1365-2494.1988.tb02153.x

Campbell, B. (1985). Winged coulter depth effects on overdrilled red clover seedling emergence. *N. Z. J. Agric. Res.* 28, 7–17. doi: 10.1080/00288233.1985.10426994

Campbell, B., and Kunelius, H. (1984). Performance of overdrilled red clover with different sowing rates and initial grazing managements. *N. Z. J. Exp. Agric.* 12, 71–81. doi: 10.1080/03015521.1984.10421415

Campbell, M., and Swain, F. (1973). Effect of strength, tilth and heterogeneity of the soil surface on radicle-entry of surface-sown seeds. *Grass Forage Sci.* 28, 41–50. doi: 10.1111/j.1365-2494.1973.tb00718.x

Caradus, J., Bouton, J., Brummer, C., Faville, M., George, R., Hume, D., et al. (2021). Plant breeding for resilient pastures. *NZGA Res. Pract. Ser.* 17, 81–104. doi: 10.33584/rps.17.2021.3441

Carswell, A., Gongadze, K., Misselbrook, T., and Wu, L. (2019). Impact of transition from permanent pasture to new swards on the nitrogen use efficiency, nitrogen and carbon budgets of beef and sheep production. *Agric. Ecosyst. Environ.* 283:106572. doi: 10.1016/j.agee.2019.106572

Cartmill, A. D., and Donaghy, D. J. (2024). Pasture performance: perspectives on plant persistence and renewal in New Zealand dairy systems. *Agronomy* 14:1673. doi: 10.3390/agronomy14081673

Casler, M. D., West, D. C., and Undersander, D. J. (1999). Establishment of temperate pasture species into alfalfa by frost-seeding. *Agron. J.* 91, 916–921. doi: 10.2134/agronj1999.916916x

Chamen, W. T., Moxey, A. P., Towers, W., Balana, B., and Hallett, P. D. (2015). Mitigating arable soil compaction: a review and analysis of available cost and benefit data. *Soil Tillage Res.* 146, 10–25. doi: 10.1016/j.still.2014.09.011

Chapman, D. F., Bryant, J. R., Olayemi, M. E., Edwards, G. R., Thorrold, B. S., Mcmillan, W. H., et al. (2017). An economically based evaluation index for perennial and short-term ryegrasses in New Zealand dairy farm systems. *Grass Forage Sci.* 72, 1–21. doi: 10.1111/gfs.12213

Charles, G. W., Blair, G. J., and Andrews, A. C. (1991). The effect of soil temperature, sowing depth and soil bulk density on the seedling emergence of tall fescue (*Festuca arundinacea* Schreb.) and white clover (*Trifolium repens* L.). *Aust. J. Agric. Res.* 42, 1261–1269. doi: 10.1071/AR9911261

Charlton, J., and Stewart, A. (2000). Timothy-the plant and its use on New Zealand farms. *Proc. N. Z. Grassl. Assoc.* 63, 147–153. doi: 10.33584/jnzg.2000.62.2365

Crush, J., Evans, J., and Cosgrove, G. (1989). Chemical composition of ryegrass (*Lolium perenne* L.) and prairie grass (*Bromus willdenowii* Kunth) pastures. *N. Z. J. Agric. Res.* 32, 461–468. doi: 10.1080/00288233.1989.10417918

Culleton, N., Murphy, W., and O'keeffe, W. (1986). The role of mixtures and seeding rate in ryegrass productivity. *Ir. J. Agric. Res.* 25, 299–306.

Cuomo, G. J., Johnson, D. G., and Head, W. A. Jr. (2001). Interseeding kura clover and birdsfoot trefoil into existing cool-season grass pastures. *Agron. J.* 93, 458–462. doi: 10.2134/agronj2001.932458x

Daly, M., Fraser, T., Perkins, A., and Moffat, C. (1999). Farmer perceptions of reasons for perennial pasture persistence and the relationship of these with management practice, species composition, and soil fertility. *Proc. N. Z. Grassl. Assoc.* 61, 9–15. doi: 10.33584/jnzg.1999.61.2348

DeBano, L. F. (2000). The role of fire and soil heating on water repellency in wildland environments: a review. *J. Hydrol.* 231-232, 195–206. doi: 10.1016/S0022-1694(00)00194-3

Derner, J. D., and Schuman, G. E. (2007). Carbon sequestration and rangelands: a synthesis of land management and precipitation effects. *J. Soil Water Conserv.* 62, 77–85. doi: 10.1080/00224561.2007.12435927

Detling, J., Dyer, M., and Winn, D. (1979). Net photosynthesis, root respiration, and regrowth of *Bouteloua gracilis* following simulated grazing. *Oecologia* 41, 127–134. doi: 10.1007/BF00344997

Donald, C. (1951). Competition among pasture plants. I. Intraspecific competition among annual pasture plants. *Aust. J. Agric. Res.* 2, 355–376. doi: 10.1071/AR9510355

Douglas, J., and Crawford, C. (1991). Wheel-induced soil compaction effects on ryegrass production and nitrogen uptake. *Grass Forage Sci.* 46, 405–416. doi: 10.1111/j.1365-2494.1991.tb02401.x

Duckett, T., Pearson, S., Blackmore, S., Grieve, B., Chen, W.-H., Cielniak, G., et al. (2018). Agricultural robotics: the future of robotic agriculture. *arXiv*.

Easton, S., Baird, D., Baxter, G., Cameron, N., Hainsworth, R., Johnston, C., et al. (1997). Annual and hybrid ryegrass cultivars in New Zealand. *Proc. N. Z. Grassl. Assoc.* 59, 239–244. doi: 10.33584/jnzg.1997.59.2248

Fenner, M. (2012). Seed ecology. Chapman and Hall, London: Springer Science & Business Media.

Fenoll, J., Ruiz, E., Flores, P., Vela, N., Hellín, P., and Navarro, S. (2011). Use of farming and agro-industrial wastes as versatile barriers in reducing pesticide leaching through soil columns. *J. Hazard. Mater.* 187, 206–212. doi: 10.1016/j.jhazmat.2011.01.012

Finn, J. A., Kirwan, L., Connolly, J., Sebastià, M. T., Helgadottir, A., Baadshaug, O. H., et al. (2013). Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: a 3-year continental-scale field experiment. *J. Appl. Ecol.* 50, 365–375. doi: 10.1111/1365-2664.12041

Fraser, M. D., Moorby, J. M., Vale, J. E., and Evans, D. M. (2014). Mixed grazing systems benefit both upland biodiversity and livestock production. *PLoS One* 9:e89054. doi: 10.1371/journal.pone.0089054

Frost, J. (1988). Effects on crop yields of machinery traffic and soil loosening: part 2, effects on grass yield of soil compaction, low ground pressure tyres and date of loosening. *J. Agric. Eng. Res.* 40, 57–69. doi: 10.1016/0021-8634(88)90119-9

Fuhlendorf, S. D., and Engle, D. M. (2001). Restoring heterogeneity on rangelands: ecosystem management based on evolutionary grazing patterns: we propose a paradigm that enhances heterogeneity instead of homogeneity to promote biological diversity and wildlife habitat on rangelands grazed by livestock. *Bioscience* 51, 625–632.

Gardner, M. J., Condon, J. R., Peoples, M. B., Conyers, M. K., Dear, B. S., and Li, G. D. (2023). Chicory stimulates companion legume species to fix more biological nitrogen. *Plant Soil* 506, 395–406. doi: 10.1007/s11104-023-06370-3

Gerard, P., Cooper, B., Eden, T., Howlett, S., Lane, P., Panckhurst, K., et al. (2009). Impact of ryegrass selection and paddock history on clover establishment in new dairy pasture. *Proc. N. Z. Grassl. Assoc.* 71, 133–137. doi: 10.33584/jnzg.2009.71.2759

Giller, K. E., Hijbeek, R., Andersson, J. A., and Sumberg, J. (2021). Regenerative agriculture: an agronomic perspective. *Outlook Agric.* 50, 13–25. doi: 10.1177/0030727021998063

Girona-García, A., Badía-Villas, D., Martí-Dalmau, C., Ortiz-Perpiñá, O., Mora, J. L., and Armas-Herrera, C. M. (2018). Effects of prescribed fire for pasture management on soil organic matter and biological properties: a 1-year study case in the Central Pyrenees. *Sci. Total Environ.* 618, 1079–1087. doi: 10.1016/j.scitotenv.2017.09.127

Glassey, C., Clark, C., Roach, C., and Lee, J. (2013). Herbicide application and direct drilling improves establishment and yield of chicory and plantain. *Grass Forage Sci.* 68, 178–185. doi: 10.1111/j.1365-2494.2012.00885.x

Gomes, M. P., da Silva Cruz, F. V., Bicalho, E. M., Borges, F. V., Fonseca, M. B., Juneau, P., et al. (2017). Effects of glyphosate acid and the glyphosate-commercial formulation (roundup) on Dimorphandra wilsonii seed germination: interference of seed respiratory metabolism. *Environ. Pollut.* 220, 452–459. doi: 10.1016/j.envpol.2016.09.087

Gordijn, P. J., and O'Connor, T. G. (2021). Multidecadal effects of fire in a grassland biodiversity hotspot: does pyrodiversity enhance plant diversity? *Ecol. Appl.* 31:e02391. doi: 10.1002/eap.2391

Greene, R., Kinnell, P., and Wood, J. (1994). Role of plant cover and stock trampling on runoff and soil-erosion from semi-arid wooded rangelands. *Aust. J. Soil Res.* 32, 953–973. doi: 10.1071/SR9940953

Greenwood, K., and McKenzie, B. (2001). Grazing effects on soil physical properties and the consequences for pastures: a review. *Aust. J. Exp. Agric.* 41, 1231–1250. doi: 10.1071/EA00102

Guretzky, J. A., Moore, K. J., Knapp, A. D., and Brummer, E. C. (2004). Emergence and survival of legumes seeded into pastures varying in landscape position. *Crop Sci.* 44, 227–233. doi: 10.2135/cropsci2004.2270

Hamza, M., and Anderson, W. K. (2005). Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil Tillage Res.* 82, 121–145. doi: 10.1016/j.still.2004.08.009

Havens, P. L., Sims, G. K., and Erhardt-Zabik, S. (2017). Fate of herbicides in the environment. *Handb. Weed Manag. Syst.*, 245–278. doi: 10.1201/9780203752470-8

Hayes, R. C., Newell, M. T., Pembleton, K. G., Peoples, M. B., and Li, G. D. (2021). Sowing configuration affects competition and persistence of lucerne (*Medicago sativa*) in mixed pasture swards. *Crop Pasture Sci.* 72, 707–722. doi: 10.1071/CP20270

Helander, M., Pauna, A., Saikkonen, K., and Saloniemi, I. (2019). Glyphosate residues in soil affect crop plant germination and growth. *Sci. Rep.* 9:19653. doi: 10.1038/s41598-019-56195-3

Hoen, K. (1968). The effect of plant size and developmental stage on summer survival of some perennial grasses. *Aust. J. Exp. Agric. Anim. Hus.* 8, 190–196. doi: 10.1071/EA9680190

Holland, E. A., and Detling, J. K. (1990). Plant response to herbivory and belowground nitrogen cycling. *Ecology* 71, 1040–1049. doi: 10.2307/1937372

Hopkins, A., Gilbey, J., Dibb, C., Bowling, P., and Murray, P. (1990). Response of permanent and reseeded grassland to fertilizer nitrogen. 1. Herbage production and herbage quality. *Grass Forage Sci.* 45, 43–55. doi: 10.1111/j.1365-2494.1990.tb02181.x

Houlbrooke, D., Thom, E., Chapman, R., and McLay, C. (1997). A study of the effects of soil bulk density on root and shoot growth of different ryegrass lines. *N. Z. J. Agric. Res.* 40, 429–435. doi: 10.1080/00288233.1997.9513265

Hughes, L. E. (2017). Plant species diversity, drought, and a grazing system on the Arizona strip. *Rangelands* 39, 20–27. doi: 10.1016/j.rala.2016.11.003

Javed, T., Afzal, I., Shabbir, R., Ikram, K., Zaheer, M. S., Faheem, M., et al. (2022). Seed coating technology: an innovative and sustainable approach for improving seed quality and crop performance. *J. Saudi Soc. Agric. Sci.* 21, 536–545. doi: 10.1016/j.jssas.2022.03.003

Känkänen, H., Mikkola, H. J., and Eriksson, C. (2001). Effect of sowing technique on growth of undersown crop and yield of spring barley. *J. Agron. Crop Sci.* 187, 127–136. doi: 10.1046/j.1439-037X.2001.00483.x

Kerr, G., Brown, J., Kilday, T., and Stevens, D. (2015). A more quantitative approach to pasture renewal. *J. N. Z. Grassl.* 77, 251–258. doi: 10.33584/jnzg.2015.77.460

Kibblewhite, M., Ritz, K., and Swift, M. (2008). Soil health in agricultural systems. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 363, 685–701. doi: 10.1098/rstb.2007.2178

Ledgard, S., Sprosen, M., Penno, J., and Rajendram, G. (2001). Nitrogen fixation by white clover in pastures grazed by dairy cows: temporal variation and effects of nitrogen fertilization. *Plant Soil* 229, 177–187. doi: 10.1023/A:1004833804002

Linhart, Y. B. (1976). Density-dependent seed germination strategies in colonizing versus non-colonizing plant species. *J. Ecol.* 64, 375–380. doi: 10.2307/2258701

Lomax, S., Colusso, P., and Clark, C. E. (2019). Does virtual fencing work for grazing dairy cattle? *Animals* 9:429. doi: 10.3390/ani9070429

Martinez, D. A., Loening, U. E., and Graham, M. C. (2018). Impacts of glyphosate-based herbicides on disease resistance and health of crops: a review. *Environ. Sci. Eur.* 30, 1–14. doi: 10.1186/s12302-018-0131-7

McCahon, K., McCahon, A., and Ussher, G. (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. *NZGA Res. Pract. Ser.* 17, 213–224. doi: 10.33584/rps.17.2021.3474

McNally, S. R., Laughlin, D. C., Rutledge, S., Dodd, M. B., Six, J., and Schipper, L. A. (2017). 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. doi: 10.1007/s11104-016-3050-7

McWilliam, J., Clements, R., and Dowling, P. (1970). Some factors influencing the germination and early seedling development of pasture plants. *Aust. J. Agric. Res.* 21, 19–32. doi: 10.1071/AR9700019

Michalk, D., Dowling, P., Kemp, D., King, W. M., Packer, I., Holst, P., et al. (2003). Sustainable grazing systems for the central tablelands, New South Wales. *Aust. J. Exp. Agric.* 43, 861–874. doi: 10.1071/EA02180

Miller, D. A. (1996). Allelopathy in forage crop systems. *Agron. J.* 88, 854–859. doi: 10.2134/agronj1996.00021962003600060003x

Moot, D., Scott, W., Roy, A., and Nicholls, A. (2000). Base temperature and thermal time requirements for germination and emergence of temperate pasture species. *N. Z. J. Agric. Res.* 43, 15–25. doi: 10.1080/00288233.2000.9513404

Morris, N., Miller, P., Orson, J., and Froud-Williams, R. (2010). The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—a review. *Soil Tillage Res.* 108, 1–15. doi: 10.1016/j.still.2010.03.004

Mueller, J., and Chamblee, D. (1984). Sod-seeding of ladino clover and alfalfa as influenced by seed placement, seeding date, and grass suppression 1. *Agron. J.* 76, 284–289. doi: 10.2134/agronj1984.00021962007600020026x

Neary, G., and Leonard, M. (2020). Effects of fire on grassland soils and water: a review. *Grasses Grassl. Aspects*, 1–22.

Oates, L. G., Undersander, D. J., Gratton, C., Bell, M. M., and Jackson, R. D. (2011). Management-intensive rotational grazing enhances forage production and quality of subhumid cool-season pastures. *Crop Sci.* 51, 892–901. doi: 10.2135/cropsci2010.04.0216

O'connor, T., Uys, R., and Mills, A. (2004). Ecological effects of fire-breaks in the montane grasslands of the southern Drakensberg, South Africa. *Afr. J. Range Forage Sci.* 21, 1–9. doi: 10.2989/10220110409485828

Ojima, D. S., Schimel, D., Parton, W., and Owensby, C. (1994). Long-and short-term effects of fire on nitrogen cycling in tallgrass prairie. *Biogeochemistry* 24, 67–84. doi: 10.1007/BF02390180

Ordóñez, I. P., López, I. F., Kemp, P. D., Donaghy, D. J., Zhang, Y., and Herrmann, P. (2021). Response of *Bromus valdivianus* (pasture brome) growth and physiology to defoliation frequency based on leaf stage development. *Agronomy* 11:2058. doi: 10.3390/agronomy11102058

Orwin, K. H., Mason, N. W., Berthet, E. T., Grelet, G., Mudge, P., and Lavorel, S. (2022). Integrating design and ecological theory to achieve adaptive diverse pastures. *Trends Ecol. Evol.* 37, 861–871. doi: 10.1016/j.tree.2022.06.006

Parsons, A., Edwards, G., Newton, P., Chapman, D., Caradus, J., Rasmussen, S., et al. (2011). Past lessons and future prospects: plant breeding for yield and persistence in cool-temperate pastures. *Grass Forage Sci.* 66, 153–172. doi: 10.1111/j.1365-2494.2011.00785.x

Paustian, K., Six, J., Elliott, E., and Hunt, H. (2000). Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry* 48, 147–163. doi: 10.1023/A:1006271331703

Pembleton, K. G., Tozer, K. N., Edwards, G. R., Jacobs, J. L., and Turner, L. R. (2015). Simple versus diverse pastures: opportunities and challenges in dairy systems. *Anim. Prod. Sci.* 55, 893–901. doi: 10.1071/AN14816

Porter, D., Lucas, R., and Andrews, M. (1993). Effects of sowing depth and additional nitrogen on emergence and establishment of a range of New Zealand pasture grasses. *Proc. Agron. Soc. N. Z.* 23, 69–74.

Praat, J., Ritchie, W., Baker, C., and Hodgson, J. (1996). Target populations for direct-drilled ryegrass and tall fescue. *Proc. N. Z. Grassl. Assoc.* 57, 77–81.

Rapiya, M., Mndela, M., Truter, W., and Ramoelo, A. (2025). Assessing the economic viability of sustainable pasture and rangeland management practices: a review. *Agriculture* 15:690. doi: 10.3390/agriculture15070690

Refshauge, G., Newell, M. T., Hopkins, D. L., Holman, B. W., Morris, S., and Hayes, R. C. (2022). The plasma and urine mineral status of lambs offered diets of perennial wheat or annual wheat, with or without lucerne. *Small Rumin. Res.* 209:106639. doi: 10.1016/j.smallrumres.2022.106639

Robinson, G., and Dowling, P. (1985). Establishment and persistence of surface-sown and resident grasses using three pasture development methods in relation to three stocking managements. *Aust. J. Exp. Agric.* 25, 562–567. doi: 10.1071/EA9850562

Rochon, J., Doyle, C., Greef, J., Hopkins, A., Molle, G., Sitzia, M., et al. (2004). Grazing legumes in Europe: a review of their status, management, benefits, research needs and future prospects. *Grass Forage Sci.* 59, 197–214. doi: 10.1111/j.1365-2494.2004.00423.x

Rollo, M., Sheath, G., Slay, M., Knight, T., Judd, T., and Thomson, N. (1998). Tall fescue and chicory for increased summer forage production. *Proc. N. Z. Grassl. Assoc.* 60, 249–253. doi: 10.33584/jnzg.1998.60.2284

Rose, T. J., Van Zwieten, L., Claassens, A., Scanlan, C., and Rose, M. T. (2018). Phytotoxicity of soilborne glyphosate residues is influenced by the method of phosphorus fertiliser application. *Plant Soil* 422, 455–465. doi: 10.1007/s11104-017-3482-8

Ross, M. A., and Harper, J. L. (1972). Occupation of biological space during seedling establishment. *J. Ecol.* 60, 77–88. doi: 10.2307/2258041

Rutledge, S., Mudge, P., Wallace, D., Campbell, D., Woodward, S., Wall, A., et al. (2014). CO2 emissions following cultivation of a temperate permanent pasture. *Agric. Ecosyst. Environ.* 184, 21–33. doi: 10.1016/j.agee.2013.11.005

Rutledge, S., Wall, A., Mudge, P., Troughton, B., Campbell, D., Pronger, J., et al. (2017). The carbon balance of temperate grasslands part II: the impact of pasture renewal via direct drilling. *Agric. Ecosyst. Environ.* 239, 132–142. doi: 10.1016/j.agee.2017.01.013

Sanderson, M. A. (2010). Stability of production and plant species diversity in managed grasslands: a retrospective study. *Basic Appl. Ecol.* 11, 216–224. doi: 10.1016/j.baae.2009.08.002

Sanderson, M., Byers, R., Skinner, R., and Elwinger, G. (2003). Growth and complexity of white clover stolons in response to biotic and abiotic stress. *Crop Sci.* 43, 2197–2205. doi: 10.2135/cropsci2003.2197

Santos, M. S., Nogueira, M. A., and Hungria, M. (2019). Microbial inoculants: reviewing the past, discussing the present and previewing an outstanding future for the use of beneficial bacteria in agriculture. *AMB Express* 9:205. doi: 10.1186/s13568-019-0932-0

Schlueter, D., and Tracy, B. (2012). Sowing method effects on clover establishment into permanent pasture. *Agron. J.* 104, 1217–1222. doi: 10.2134/agronj2012.0035

Schuman, G., Reeder, J., Manley, J., Hart, R., and Manley, W. (1999). Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. *Ecol. Appl.* 9, 65–71. doi: 10.1890/1051-0761(1999)009[0065:IOGMOT]2.0.CO;2

Scott, J., Lodge, G., and McCormick, L. (2000). Economics of increasing the persistence of sown pastures: costs, stocking rate and cash flow. *Aust. J. Exp. Agric.* 40, 313–323. doi: 10.1071/EA98016

Shafi, U., Mumtaz, R., García-Nieto, J., Hassan, S. A., Zaidi, S. A. R., and Iqbal, N. (2019). Precision agriculture techniques and practices: from considerations to applications. *Sensors* 19:3796. doi: 10.3390/s19173796

Silburn, D. M., Carroll, C., Ciesiolka, C. A., DeVoil, R., and Burger, P. (2011). Hillslope runoff and erosion on duplex soils in grazing lands in semi-arid Central Queensland. I. Influences of cover, slope, and soil. *Soil Res.* 49, 105–117. doi: 10.1071/SR09068

Singh, S., Kumar, V., Datta, S., Wani, A. B., Dhanjal, D. S., Romero, R., et al. (2020). Glyphosate uptake, translocation, resistance emergence in crops, analytical monitoring, toxicity and degradation: a review. *Environ. Chem. Lett.* 18, 663–702. doi: 10.1007/s10311-020-00969-z

Sishodia, R. P., Ray, R. L., and Singh, S. K. (2020). Applications of remote sensing in precision agriculture: a review. *Remote Sens* 12:3136. doi: 10.3390/rs12193136

Skinner, R. H. (2005). Emergence and survival of pasture species sown in monocultures or mixtures. *Agron. J.* 97, 799–805. doi: 10.2134/agronj2004.0211

Skinner, R. H., and Dell, C. J. (2016). Yield and soil carbon sequestration in grazed pastures sown with two or five forage species. *Crop Sci.* 56, 2035–2044. doi: 10.2135/cropsci2015.11.0711

Smith, A., and Martin, L. (1994). Allelopathic characteristics of three cool-season grass species in the forage ecosystem. *Agron. J.* 86, 243–246. doi: 10.2134/agronj1994.00021962008600020006x

Stevens, D., and Knowles, I. (2011). Identifying the need for pasture renewal and valuing the contribution of renewal on a dairy farm-Telford dairy, a case study. *NZGA Res. Pract. Ser.* 15, 211–216. doi: 10.33584/rps.15.2011.3204

Stewart, A. (1996). Potential value of some *Bromus* species of the section *Ceratochloa*. *N. Z. J. Agric. Res.* 39, 611–618. doi: 10.1080/00288233.1996.9513220

Taylor, T., Foote, J., Snyder, J., Smith, E., and Templeton, W. Jr. (1972). Legume seedlings stands resulting from winter and spring sowings in Kentucky bluegrass (*Poa pratensis* L.) sod 1. *Agron. J.* 64, 535–538. doi: 10.2134/agronj1972.00021962006400040037x

Taylor, T., Smith, E., and Templeton, W. Jr. (1969). Use of minimum tillage and herbicide for establishing legumes in Kentucky bluegrass (*Poa pratensis* L.) swards 1. *Agron. J.* 61, 761–766. doi: 10.2134/agronj1969.00021962006100050033x

Teague, R., and Kreuter, U. (2020). Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Front. Sustain. Food Syst.* 4:534187. doi: 10.3389/fsufs.2020.534187

Thom, E., Fraser, T., and Hume, D. (2011). Sowing methods for successful pasture establishment-a review. *NZGA Res. Pract. Ser.* 15, 31–37. doi: 10.33584/rps.15.2011.3217

Thom, E., Thomson, N., and Clayton, D. (1985). Establishment and management of suitable species in dairy pastures. *NZGA Res. Pract. Ser.* 3, 71–75. doi: 10.33584/rps.3.1985.3317

Tozer, K., Cameron, C., and Thom, E. (2011). Pasture persistence: farmer observations and field measurements. *NZGA Res. Pract. Ser.* 15, 25–30. doi: 10.33584/rps.15.2011.3216

Tozer, K., and Douglas, G. (2016). Pasture establishment on non-cultivable hill country: a review of the New Zealand literature. *NZGA Res. Pract. Ser.* 16, 213–224. doi: 10.33584/rps.16.2016.3233

Tozer, K., Douglas, G., Moss, R., Rennie, G., Knight, T., Cameron, C., et al. (2016). Effect of seed mix, sowing time, summer fallow, site location and aspect on the establishment of sown pasture species on uncultivable hill country. *N. Z. J. Agric. Res.* 59, 389–411. doi: 10.1080/00288233.2016.1224768

Vasta, V., Daghio, M., Cappucci, A., Buccioni, A., Serra, A., Viti, C., et al. (2019). Invited review: plant polyphenols and rumen microbiota responsible for fatty acid biohydrogenation, fiber digestion, and methane emission: experimental evidence and methodological approaches. *J. Dairy Sci.* 102, 3781–3804. doi: 10.3168/jds.2018-14985

Verdon, M., Langworthy, A., and Rawnsley, R. (2021). Virtual fencing technology to intensively graze lactating dairy cattle. II: effects on cow welfare and behavior. *J. Dairy Sci.* 104, 7084–7094. doi: 10.3168/jds.2020-19797

Vermeire, L. T., Mitchell, R. B., Fuhlendorf, S. D., and Gillen, R. L. (2004). Patch burning effects on grazing distribution. *J. Range Manag.* 57, 248–252. doi: 10.2307/4003792

Waite, S., and Hutchings, M. J. (1978). The effects of sowing density, salinity and substrate upon the germination of seeds of *Plantago coronopus* L. *New Phytol.* 81, 341–348. doi: 10.1111/j.1469-8137.1978.tb02639.x

Wall, A. M., Laubach, J., Campbell, D. I., Goodrich, J. P., Graham, S. L., Hunt, J. E., et al. (2024). Effects of dairy farming management practices on carbon balances in New Zealand's grazed grasslands: synthesis from 68 site-years. *Agric. Ecosyst. Environ.* 367:108962. doi: 10.1016/j.agee.2024.108962

Wardle, D., Nicholson, K., and Rahman, A. (1996). Use of a comparative approach to identify allelopathic potential and relationship between allelopathy bioassays and "competition" experiments for ten grassland and plant species. *J. Chem. Ecol.* 22, 933–948. doi: 10.1007/BF02029946

Watkin, B. (1974). The performance of pasture species in Canterbury. *Proc. N. Z. Grassl. Assoc.* 36, 180–190. doi: 10.33584/jnzg.1974.36.1387

Wen, Y., and Jiang, H. F. (2005). Cutting effects on growth characteristics, yield composition, and population relationships of perennial ryegrass and white clover in mixed pasture. *N. Z. J. Agric. Res.* 48, 349–358. doi: 10.1080/00288233.2005.9513666

Wilson, J. B. (1988). Shoot competition and root competition. *J. Appl. Ecol.* 25, 279–296. doi: 10.2307/2403626