CSIRO PUBLISHING

SPECIAL ISSUE: RAAN-A 2023 | REVIEW
https://doi.org/10.1071/AN23066

ANIMAL PRODUCTION SCIENCE

Multispecies forages in the Australian dairy feedbase: is there a biological business case?

Anna L. Thomson[A,*] and Rodrigo I. Albornoz[B]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Anna L. Thomson
Agriculture Victoria Research, Ellinbank Smart Farm, 1301 Hazeldean Road, Ellinbank, Vic. 3821, Australia
Email: anna.thomson@agriculture.vic.gov.au

Handling Editor:
David Masters

Received: 8 February 2023
Accepted: 16 June 2023
Published: 11 July 2023

Cite this:
Thomson AL and Albornoz RI (2023) *Animal Production Science*, **63**(18), 1958–1969.
doi:10.1071/AN23066

ABSTRACT

This review considers the potential role of multispecies swards in de-risking Australian dairy systems that currently rely heavily on monocultures of perennial ryegrass and high rates of inorganic nitrogen application to be productive. Recent trends in increasing inorganic nitrogen fertiliser prices, societal pressure for increased environmental sustainability of farming practices, coupled with variable and extreme weather events have renewed interest for functionally diverse pasture mixtures. Evidence from the latest international studies either for or against the purported benefits of multispecies swards (e.g. productive, resilient, and environmentally positive) is examined. There is an ever-growing body of evidence confirming that species richness can promote high levels of productivity at low or zero rates of nitrogen fertiliser application, often with increasingly positive effects as species richness increases. However, results within and between different levels of species richness are not always consistent, suggesting that not all multispecies swards will perform alike, even at a constant level of functional diversity. A multitude of other factors is presented that interact to determine the success of one multispecies sward over another. These include soil type and fertility, species choice, functional group proportions, sward management under either grazing or cutting, fertiliser regimes, and grazing management practices. It was concluded that this complexity gives rise to a need for further research into the biological mechanisms behind multispecies mixtures to determine the factors, other than simply species richness, that will guarantee success as more farmers inevitably search for alternatives to perennial ryegrass pasture in the Australian dairy farming industry.

Keywords: Australian, dairy, diverse swards, forages mixtures, herbal leys, milk production, mixed forages, multispecies forages.

Introduction

Globally, it is estimated that 1 billion hectares, 7% of the total land area of Earth, is devoted to dairy production (FAO 2016). Most of this land area is grassland, used either for grazing or as a source of conserved forage. A need to intensify milk production to meet global demand, combined with plentiful and inexpensive access to inorganic nitrogen (N) fertiliser, has resulted in a preference to sow dairy grassland with monoculture species that display a linear yield response to inorganic N fertiliser application (Oenema *et al.* 2014). The species of choice in most temperate Australian dairy systems is perennial ryegrass (*Lolium perenne; PRG*), a species that has benefitted from significant genetic improvement in targeted plant breeding programs to optimise its productivity and nutritive value for grazing livestock (Lee *et al.* 2014). However, in recent years a combination of fluctuating and extreme prices of inorganic N fertilisers (Humphreys *et al.* 2012), combined with restrictions on N fertiliser rates per hectare per annum in certain countries (e.g. Water Framework Directive in the EU), and societal pressure to reduce environmental impacts (Martínez-Dalmau *et al.* 2021), have combined to create a driver for farmers to consider the reintroduction of functional diversity to their pastures. The most common example of this is the addition of clover to PRG pastures creating a binary mixture (Humphreys *et al.* 2017). In the late 1990s, research suggested that further increases in diversity were beneficial (Hector *et al.* 1999), leading to the concept of targeted multispecies swards becoming a topic of scientific interest in the 2000s until the present day. Hector *et al.* (1999) conducted a foundational study involving eight field sites across Europe that showed an overall correlation between an increase of functional groups and increased pasture productivity in the absence of confounding effects of N fertilisation. Further research into multispecies swards grew in more recent years from this finding that diversity can increase yield, partly or entirely replacing the need for N fertilisation, thus creating a cheaper and more self-reliant way of intensifying grassland productivity (Döring *et al.* 2013; Finn *et al.* 2013). Such swards, in the modern context, are defined in this review as temporary pastures (4–6 years) designed to incorporate several species from multiple functional groups in harmony, such that different species fill different ecological niches resulting in complementarity effects. The functional groups most often represented are perennial grasses, legumes, and herbs (forbs), comprising species that have nutritional value for feeding livestock; however, brassicas, cereals, or annual pasture species may also be featured. Multispecies swards have also been known by other names in the literature, including 'mixed swards', 'herbal leys', or 'diverse forages'. The purported benefits of modern multispecies swards are threefold, namely, productive (Jaramillo *et al.* 2021), resilient (Lüscher *et al.* 2022), and environmentally beneficial (Huyghe *et al.* 2012). Productivity as a defining feature is key because it excludes sward types from this review that, although diverse, are not sown with the aim of producing high yields, such as, for example, meadowlands, permanent pasture, and agri-environmental mixtures comprising wildflowers.

This review identifies both opportunities and challenges related to the incorporation of multispecies swards into temperate Australian dairy systems and builds on historical reviews of this topic (Pembleton *et al.* 2015) by incorporating more recent international studies. Dairy farming in Australia is largely concentrated in southern temperate regions where cattle graze all year round due to relatively mild winters. Systems are divided between irrigated and rain-fed, or can be a mixture of both, depending on the available water sources in each dairying region. A current lack of Australian government policy controlling inorganic N application rates has resulted in monoculture PRG remaining the most common pasture sward within temperate dairy farming systems, unlike many other similarly temperate dairying nations that routinely combine legumes and grasses (e.g. New Zealand, Ireland). A 2019 national industry survey (Dairy Australia 2019) reported that 67% of respondents had sown PRG, and 65% had sown an annual or short-term ryegrass (e.g. Italian ryegrass), in the past 5 years. Only 12% reported sowing clover and just 5% had sown a mixed sward in the past 5 years, indicating little use of binary mixtures with clover, or more diverse swards in general. However, the same economic pressures (e.g. N fertiliser price volatility and water scarcity in drought years) that have driven interest in pasture diversity overseas, combined with the possibility of greater restrictions around N applications in Australia in the future (Rawnsley *et al.* 2019), are now fuelling rising interest in multispecies pastures among Australian dairy producers and thus a review is timely to re-assess their potential.

Soil–plant interactions under multispecies swards

One of the first considerations influencing the uptake of multispecies swards in southern Australian dairying regions is whether the soils found in these regions can support multispecies sward growth, since they are typically either moderately or very acidic, such as in the State of Victoria where over 50% of all Australian milk is produced (Dairy Australia 2019; Fig. 1). A recent UK study contrasted multispecies sward productivity on two soil types, pH 5.4 and 7.4 (measured in water), where soil was removed from the paddock and placed in pots for a growth study (Darch *et al.* 2022). Darch *et al.* (2022) observed that a mixture of 15 perennial species (six grasses, five legumes and four herbs) yielded both greater total dry matter (DM) per pot and greater DM per functional group per pot in all three functional groups using the pH 5.4 soil than the pH 7.4 soil. Further examination of soil properties by Darch *et al.* (2022) showed a greater concentration of soil organic carbon, and soil N (as total oxidisable N plus ammonium N) in the pH 5.4 soil, which may have contributed to this outcome. The relative success of the more acidic soil type in the study of Darch *et al.* (2022) is promising for the application of multispecies swards in Australia. The functional group most likely to suffer in acidic soils is legumes. Determining the pre- and post-establishment fertiliser and liming requirements for a multispecies sward can be more complicated than with a monoculture where the needs of only one plant needs to be accounted for (Bolland and Russell 2010). Hill *et al.* (2005) demonstrated that phosphorus (P) requirement can differ significantly among common Australian pasture species, including legumes and grasses, and that a deficiency in P provision can alter a sward botanical composition to favour plants better adapted to nutrient stress. Furthermore, as plant communities become more complex, a greater range of micronutrients should also be considered in addition to macronutrients. For example, the rhizobia-driven N-fixing ability of certain legumes has been shown to be inhibited in boron-deficient soils (Hamilton *et al.* 2015). Another study conducted in southern Australian pastures also identified copper, molybdenum and zinc as being important to legume productivity (Brennan *et al.* 2019).

To achieve the purported efficiency benefits of multispecies swards, legumes must be utilised to fix atmospheric N in the soil, resulting in a reduced need for expensive

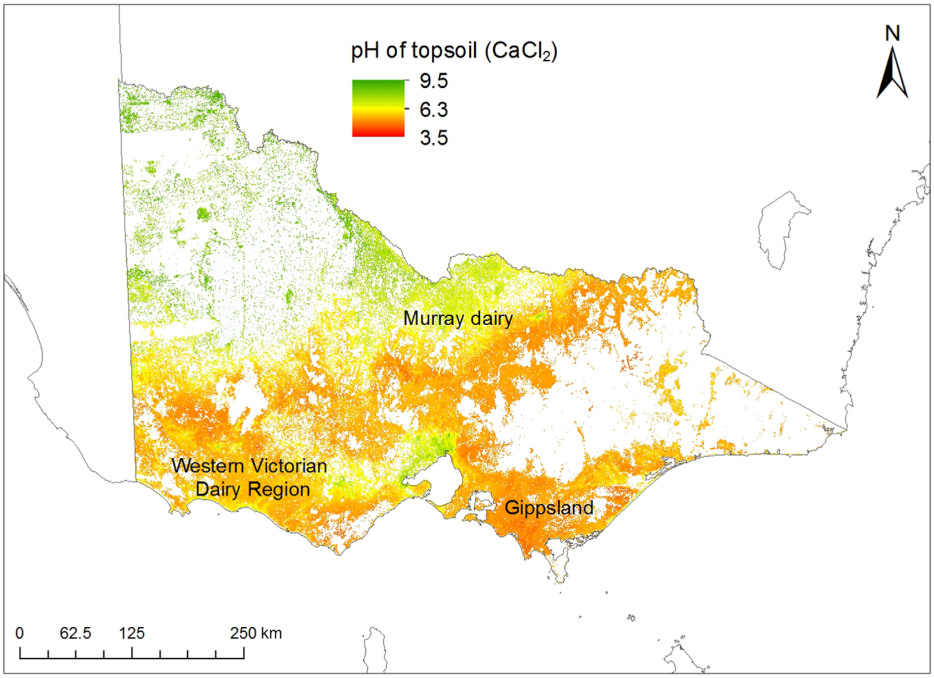

Fig. 1. A map of Victoria, Australia, showing the pH of topsoil (0–10 cm) in areas identified to have pasture as the land use, according to the 'VLUIS' land registry database (source: https://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/vrohome).

inorganic N fertiliser application (Suter *et al.* 2015). Fixed N can be transferred from the legumes to the non-legumes in the mixture through various pathways, including decomposition of legume root tissue, root exudates comprising soluble N compounds, and via mycorrhizal systems (Thilakarathna *et al.* 2016). This transfer of N from legumes to grasses and herbs within multispecies swards is an example of niche complementarity. Previous studies have measured N derived from symbiotic sources in legume-containing mixtures in excess of 200 kg N/ha.annum, a rate that completely negates the need for additional inorganic N application (Nyfeler *et al.* 2011). However, there is a risk that practitioners will continue to apply inappropriately high inorganic N fertiliser rates to multispecies swards with high concentrations of fixed N in the soil, which would lead to N loss to the environment as leached nitrate and as gaseous compounds, namely, nitrous oxide, ammonia, dinitrogen, and nitric oxide (Bracken *et al.* 2020; Bracken *et al.* 2022). Nitrous oxide is a potent greenhouse gas (GHG) and therefore any environmental benefits of multispecies swards could be negated should they lead to increased GHG emissions. In an Irish study, Bracken *et al.* (2020) first demonstrated that a mixture comprising 75% grass and 25% legume resulted in a cumulative release of ~50 g N_2O-N/ha in the 2 months post-fertilisation with 40 kg N/ha, whereas a mixture comprising 25% grass and 75% legume resulted in ~150 g N_2O-N/ha released when both swards were fertilised at the same rate. However, in a follow-up study by Bracken *et al.* (2022), where the study was repeated but with reducing fertiliser rates matched to sward legume content, PRG monocultures fertilised at 250 kg N/ha.annum produced a 71% increase in N_2O emissions relative to a legume-heavy mixture receiving no N fertiliser. Since Bracken *et al.* (2022) reported no significant difference in the herbage yield achieved from these two treatments, the mixture resulted in the least GHG emission for the same biomass yield. A different study by Cummins *et al.* (2021) agreed with this finding and further demonstrated that N_2O reduction through multispecies sward use was greater when the functional group proportions of the mixture were even and lesser in legume-dominant mixtures. Bracken *et al.* (2020, 2022) also found that the herb ribwort plantain (*Plantago lanceolota*) seemed to partially inhibit nitrification processes in soil, with small beneficial effects on N losses. However, the finding was not consistent with other studies (Podolyan *et al.* 2020). Further research is warranted to assist producers in correctly matching N fertilisation levels to multispecies sward compositions where legume concentrations can vary considerably from season to season and year to year.

Another purported benefit of introducing diverse communities of species is that key soil characteristics (other than plant available N) can be improved to provide positive long-term impacts on soil function. Such characteristics include soil structure, water-holding capacity, and soil carbon (C) concentration. A German study (the Jena Experiment) that aimed to reintroduce permanent diverse grasslands into land that was previously used for arable cropping showed a strong correlation between species richness and C sequestered after 9 years of the experiment (Lange *et al.* 2015). However, conflicting evidence has arisen on whether temporary, intensive multispecies leys can have the same beneficial soil effects. A UK study investigating three mixtures of increasing species richness compared with a monoculture PRG control showed no discernible evidence for increased soil C after 2 years under mixed swards, in comparison to the control sward (Shepperd *et al.* 2020). This was consistent with a US study by Skinner *et al.* (2006) that measured change in soil C under three different mixtures of varying diversity over 3 years and found no change or even decreases in soil C. However, in a longer-term study, conducted by the same US researchers, in which soil changes were evaluated after 9 years under a two- or five-species mixture, the more diverse mixture was shown to have more than three times the soil C accumulation rate of the binary mixture (1.80 vs 0.50 Mg C/ha.annum; Skinner and Dell 2016). Results pointed to functional diversity needing to be maintained for many years before a significant soil C concentration change can be observed. This is also likely to be associated with other factors such as previous paddock history, soil type, grazing practices, and water availability. Equally important is the assessment of C fractions, given the different contributions to soil functionality and C retention. There is evidence to show that multispecies swards result in greater root mass and rooting depth than do grass species alone (McNally *et al.* 2015; Eisenhauer *et al.* 2017), particularly compared with PRG due to its particularly shallow rooting nature. Deeper rooting structures coupled with a faster turnover of root material can explain the mechanism by which multispecies swards may increase soil organic C stocks over time. McNally *et al.* (2015) demonstrated that a moderately diverse pasture not only had deeper rooting system than a two-species mixture, but also had twice the annual root turnover (5411 vs 2672 kg/ha). Deeper rooting systems are also associated with improved soil structure and ability to adapt to and withstand drought (Hoekstra *et al.* 2015). With future climate conditions predicted to result in more extreme weather events, the ability to withstand drought is an especially important pasture characteristic for Australian dairy farms.

Many of the interactions discussed above are governed by soil microbial populations, including the degree of N fixation achieved (Unkovich 2012), carbon sequestration (Lange *et al.* 2015), and the amount of denitrification that occurs in the soil (des Roseaux *et al.* 2022). However, it has only been in recent years that analytical capability to describe microbial populations, particularly in the rhizosphere, has evolved and findings on factors that affect the soil microbiome have started to emerge. Gaining a greater mechanistic understanding of this area in relation to multispecies swards is a promising topic for further research and may help explain conflicting results on soil C sequestration under multispecies swards.

Species selection and seed mixture design

The agronomy of multispecies swards begins in the establishment phase when practitioners must initially decide on a seed mixture for the new sward. Even at this early stage, already a complex array of factors must be considered, including the total number of species (species richness), the specific species to be included, the proportional seed rate of each species within the mixture (determined by the desired botanical composition for the new sward), and finally, the seed rate per hectare at which to sow the seed mixture. A further complication is dealing with any weeds that arise, especially in Australian soil where the seedbank of weeds can be prolific, and with limited chemical weed control options due to the diversity of the sown species. Multiple authors have remarked that species richness alone does not guarantee productivity in multispecies swards, rather, objective species choice from the start is crucial for eventual success (Huyghe *et al.* 2012; Chapagain *et al.* 2020; Jordon *et al.* 2022). Notably, the number of studies focussing on how exactly to achieve the optimum seed mixture is limited. There are a greater number of studies that have compared effects of species richness on productivity (Hector *et al.* 1999; Grace *et al.* 2019*a*; Barker *et al.* 2021; Komainda *et al.* 2022) than the number of studies that have focussed on species choice (Ozcan *et al.* 2015) or functional group proportion (Finn *et al.* 2013; Grace *et al.* 2018*a*). Still fewer studies report differential effects of establishment methods for multispecies swards (e.g. seed rate at sowing, soil preparation or sowing method).

Fig. 2 shows a summary of the species included within seven previous studies. These previous studies all concerned the effect of species choice on subsequent botanical composition and sward performance. The seven studies were all conducted in Ireland, the UK, or Europe; however, many of the species utilised can be commonly purchased as commercial seed worldwide, including in Australia (except for certain herb species). The most popular species within key functional groups were PRG, cocksfoot (*Dactylis glomerata*) and timothy (*Phleum pratense*) for the grasses; white clover (*Trifolium repens*), red clover (*Trifolium pratense*) and birdsfoot trefoil (*Lotus corniculatus*) for the legumes; and ribwort plantain (*Plantago lanceolota*), yarrow (*Achillea millefolium*), chicory (*Cichorium intybus*), and burnet (*Sanguisorba minor*) for the herbs. A commonality among the studies in Fig. 2 is that they, mostly, use species that have undergone some cultivar testing and development as opposed to the use of native species when designing mixtures. Aside from PRG and certain clovers that have been extensively selectively bred, many species in Fig. 2 still represent untapped genetic potential that could be further exploited to increase their survivability and productivity within specified multispecies swards. Fig. 2 also highlights a gap in European research around the use of annual functional groups such as

Location	Treatments	All species utilised	Citation
Europe	Species richness	Browntop bent, meadow foxtail, sweet vernal grass, tall oat grass, cocksfoot, red fescue, velvet grass, perennial ryegrass, Birdsfoot trefoil, red clover, white clover, Sorrel, ribwort plantain, yarrow	Hector et al. (1999)
Europe	Functional group proportion Location	Cocksfoot, tall fescue, perennial ryegrass italian ryegrass, timothy, kentucky bluegrass, Burr medic, kura clover, red clover, white clover	Finn et al. (2013)
Turkey	Grass species choice	Perennial ryegrass, cocksfoot, tall fescue, Birdsfoot trefoil, white clover	Ozcan et al. (2015)
Ireland	Functional group proportion Nitrogen application rate	Perennial ryegrass, timothy, cocksfoot, White clover, red clover, birdsfoot trefoil, Ribwort plantain, chicory, yarrow	Grace et al. (2018a)
Ireland	Species richness Defoliation method	Perennial ryegrass, timothy, cocksfoot, White clover, red clover, birdsfoot trefoil, Ribwort plantain, chicory, yarrow	Grace et al. (2019a)
UK	Species richness	Perennial ryegrass, timothy, cocksfoot, festulolium, tall fescue, meadow fescue, Red clover white clover, alsike clover, sweet clover, sainfoin, birdsfoot trefoil, lucerne, black medick, Ribwort plantain, chicory, yarrow, burnet, sheep's parsley	Barker et al. (2021)
Germany	Species richness	Perennial ryegrass, meadow fescue, timothy, meadow grass, cocksfoot, White clover, red clover, sainfoin, birdsfoot trefoil, lucerne, persian clover, burnet, yarrow, Ribwort plantain, sheep's parsley, sorrel, black knapweed, burnet	Komainda, Muto and Isselstein (2022)

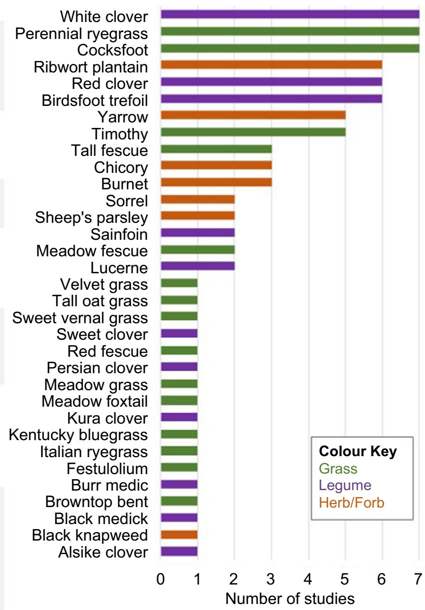

Fig. 2. A table of seven studies concerning multispecies swards and the species chosen to form treatment mixtures in those studies (left) and a graphical summary of how often each species featured in treatment mixtures across those studies (right).

brassicas and cereals that can be sown together with grasses, legumes, or herbs, or even oversown into existing perennial swards annually to make short-term multispecies mixtures. Given the harsh summer conditions in parts of Australia, the use of annuals to formulate multispecies swards may be an attractive local option, providing that farmers are happy to reseed large areas of their farms each year.

Regarding species richness, several studies agree that greater diversity increases potential complementarity effects (Jordon *et al.* 2022). Early studies focussed on proof-of-concept that moderate levels of diversity promoted greater productivity than monocultures. The terms ‘overyielding’ or ‘transgressive overyielding’ refer to a mixture either outperforming the weighted average of its constituent species sown in monoculture or outperforming the most productive constituent species sown in monoculture respectively. In the 3-year study of Finn *et al.* (2013), in which the same plot study design comparing four-species mixtures with accompanying monoculture plots of their constituent species was replicated at 31 sites across Europe, 97% of mixtures showed overyielding and 60% showed transgressive overyielding. Further to this, there are also numerous examples in the literature of multispecies swards receiving low (<100 kg N/ha.year) or no N fertiliser equalling or exceeding the yields of monoculture PRG swards receiving high (>200 kg N/ha.year) rates of applied N (Collins *et al.* 2014; Barker *et al.* 2021; Baker *et al.* 2023). More recent studies have sought to ascertain the optimum level of diversity, considering mixtures with greater richness of species; for example, Barker *et al.* (2021) observed superior yield from 12- to 17-species mixtures than from six-species mixtures.

Finn *et al.* (2013) also reported a correlation between a greater magnitude of overyielding effects and greater evenness in the functional group proportions within the mixtures. However, it has been demonstrated that the species proportions within mixtures vary dynamically over time (Barker *et al.* 2021), likely due to environmental conditions, varying establishment and persistence profiles of the different species, and cyclic N fluxes linked to legume growth patterns. While certain management interventions could be implemented to influence species proportions (for example, the withholding of inorganic N fertiliser to favour legumes over grasses, or oversowing seed of a certain missing species), it is not clear whether taking such interventions are worthwhile as opposed to working with the sward that has naturally developed over time.

Management of multispecies swards as a feed source

Most temperate Australian dairy farming systems are characterised by all-year-round grazing, with reliance on forage conservation, as silage, to manage pasture accumulation excess to animal requirements. This silage can be offered during the summer months to ensure supply of forage to the animals in adequate quantity and quality during challenging drought periods. However, studies that have compared the effects of grazing or cutting on multispecies sward botanical composition and productivity often note negative outcomes associated with grazing (Collins *et al.* 2014; Grace *et al.* 2019*b*). Grace *et al.* (2019*b*) observed an average yield reduction of 1.9 t DM/ha.annum in grazed multispecies swards versus cut multispecies swards, while there was no significant difference attributed to defoliation method in a PRG control. Collins *et al.* (2014) also observed a yield penalty in the region of 4 t DM/ha.annum associated with grazing versus cutting of a multispecies sward at one experimental location in Wales, but not at two others in Europe, and concluded that the response to grazing depended on sward composition as well as the grazing animal species (ewes at the Wales site, and dairy or beef at the European sites). A contrasting result was obtained in a recent German study, where the average 2-year productivity of an eight-species mixture was 2.7 t DM/ha.annum greater under a grazing regime than a cutting regime (Loges *et al.* 2020). Success under grazing is likely to depend on a combination of initial species choice, management (e.g. applied fertiliser/natural fertilisation through defecation), and grazing practices (e.g. defoliation frequency) determining whether additional species remain productive and persistent over time (Pembleton *et al.* 2015). This is especially the case for legumes in species-diverse swards that have a greater requirement for phosphorus and sulfur fertilisers than N and may require adapted grazing strategies suited to the legume species and cultivar and the grazing ruminant species to maintain the legume component in the sward (Frame and Newbould 1986; Black *et al.* 2009). Herb species, excluding chicory and plantain, may also be fragile and poorly suited to persistence under grazing due to effects of trampling or hard grazing. Since continuation of diversity-driven overyielding effects over a period of several years requires that diversity is maintained over time (Nyfeler *et al.* 2009), a loss of diversity under grazing may be the cause of the poorer performance of grazed multispecies swards in the afore-mentioned studies, where grazed swards yielded less than cut multispecies swards. In a grazing study, Sanderson *et al.* (2005) highlighted that continual re-establishment of the chicory and legume components in the pasture was necessary to retain the yield benefits of their complex mixtures. Australian graziers should be aware that multi-species swards may suffer some yield depression when grazed, as opposed to cut, if species loss occurs due to trampling or hard-grazing and further work into species choice for robustness and persistence under grazing is warranted to minimise this effect. There is also a need for research works that continue to monitor pastures over a longer period of up to 6 years, since few studies continue to observe swards, particularly under grazing, until the end of their productive lifetimes to measure persistence.

One purported advantage of multispecies swards in a grazing rotation is their year-round productivity and ability to produce biomass during challenging 'shoulder-seasons' (summer and winter) when PRG growth rates tend to be minimal due to unfavourable climatic conditions. In a grazing study in USA, Sanderson *et al.* (2005) concluded that planting a mixture of grasses, legumes, and chicory benefits herbage production during dry years and reduces weed invasion for a few years after planting. However, Sanderson *et al.* (2005) also observed variation within the response of different mixtures to dry conditions as one mixture produced less average herbage yield for the grazing seasons than did other mixtures (4800 vs 7600 kg DM/ha). When rain was plentiful there were no differences in herbage yield among the mixtures, all averaging 9800 kg DM/ha. This agrees with a 3-year UK study by Barker *et al.* (2021), in which it was reported that multispecies swards receiving no N fertiliser yielded less than N-fertilised perennial rye grass (PRG) in the first year when rain was plentiful, had equal yield to PRG in the second year when there was summer drought, and exceeded the yield of PRG in year 3 when there was a second summer drought. Furthermore, in the USA, Skinner *et al.* (2004) found that complex 5-species mixtures yielded more herbage than a simple 2-species mixture under dry conditions, highlighting that the vigorous growth of chicory in the complex mixture accounted for most of the yield increase, likely due to its deep-rooted growth habit allowing access to moisture from lower in the soil profile. These studies underlined the possible drought tolerance of multispecies swards and their potential to aid farmers to continue grazing without needing to offer additional conserved forage or purchased supplements through 'shoulder-seasons', and particularly in summer drought periods.

A key aspect of any grazed pasture is its nutritive characteristics in terms of macronutrients such as crude and metabolisable protein, digestibility and metabolisable energy, fibrous components, and sugars. The concentration profile of macronutrients in the forage has direct effects on eventual milk yield and milk solid concentration in the grazing dairy cow as well as pasture palatability, which further affects forage intake, utilisation and selective grazing behaviours. The selective breeding of PRG has led to the development of cultivars that are highly digestible, with high crude protein concentrations, providing grazing occurs at an ideal stage of maturity, making it an ideal nutrient-dense feed. In contrast, when PRG plants encounter environmental challenges such as prolonged high temperature and drought, typical of the Australian summer, their nutritive value has been demonstrated to decline (Rogers *et al.* 2022). However, it should be noted that there is a lack of sufficient studies that examine the effect of challenging climatic conditions on this contrast. Studies have reported nutritive values for multispecies swards in comparison to either PRG alone (Grace *et al.* 2018*b*; Barker *et al.* 2021) or in simple combinations with clover (Jing *et al.* 2017; Loges *et al.* 2020; Hearn *et al.* 2022). Loges *et al.* (2020) found that an eight-species mixture had, on average, marginally lower metabolisable energy (11.0 vs 11.1 MJ/kg DM) and crude protein concentration (21.3 vs 22.5% DM) pre-grazing than did a PRG and white clover combination over 2 years. However, these differences, while significant, were not considered large enough to affect the productivity of grazing animals and both swards were considered to produce high-quality forage. Loges *et al.* (2020) also observed that, when grazed at an optimal maturity stage, cattle preferred the more diverse multispecies sward leading to greater forage utilisation (pre-grazing minus post-grazing mass) of 9.03 t DM/ha.annum utilised for the diverse treatments versus 8.41 t DM/ha.annum utilised for the ryegrass–clover treatment. Similarly, Jing *et al.* (2017) noted a small reduction in both *in vitro* organic-matter digestibility and crude protein concentration of cut herbage in a 12-species mixture, compared with a three-species mixture of grass and two clovers; however, the reduction was small and inconsistent over cuts and years. Hearn *et al.* (2022) furthered this work by considering seasonal variation of nutritive value in both binary and complex mixtures (up to five species) and found there to be significant effects of both timepoint and pasture type but no interaction between these two for organic-matter digestibility. This lack of interaction was because all pasture types were found to have lower digestibility in summer than during the rest of the year. Furthermore, Grace *et al.* (2018*b*) compared the nutritive characteristics of a PRG monoculture and a six- and nine-species mixtures under grazing in spring, summer and autumn, and found no significant differences apart from a significant increase in crude protein concentration in the six-species mixture relative to the PRG monoculture in spring. From these studies, the evidence suggests that multispecies swards are likely to be either equally, or slightly less, nutritious than the conventional monoculture grasslands typically found currently in temperate Australian dairy farms. One explanation for reductions in nutritive quality versus PRG pasture can include certain species becoming mature and unpalatable, such as, for example, if chicory enters the reproductive stage. This scenario can also lead to undesirable selective grazing behaviours and was noted by UK farmers as a key drawback of multispecies swards when tried to implement in practice (Jordon *et al.* 2023). However, if DM yield increases are seen under multispecies swards, then it is possible that multispecies swards could still result in greater yield of nutrients per hectare despite having similar or lower nutrient concentration profiles than does traditional pasture. Indeed, evidence from a modelling study conducted in New Zealand has suggested that the nutrient profile of diverse pastures might better match N and energy requirements of cattle than that of traditional pasture types, leading to less excess N wastage in urine (Beukes *et al.* 2014). This effect combined with a lower DM concentration of diverse swards promoting dilute urine was suggested by Beukes *et al.* (2014) to lead to N leaching reductions of 11–19%, depending on the proportion of farm sown to diverse swards in the modelled scenarios. However, further work to definitively show how this effect translates to actual farming conditions is needed.

Production, health, and environmental footprint of grazing dairy cattle

Different research groups have demonstrated that diversifying the grazing sward from grass alone, or in combination with a legume, by inclusion of one or more herb species can modulate milk production and composition, but results from the literature are not consistent (Chapman *et al.* 2008; Bryant *et al.* 2017; Dodd *et al.* 2019). Two recent meta-analyses, including studies conducted predominantly in New Zealand and Australia, have reported that inclusion of chicory and/or ribwort plantain (McCarthy *et al.* 2020) or plantain alone (Nguyen *et al.* 2022) to grass or grass plus legume swards increased yields of milk and milk protein (1.20 and 1.02 kg/day, and 0.05 and 0.02 kg/day respectively), with milk fat yield being increased in the analysis including multiple herbs (0.04 kg/day) but not with plantain alone, compared with cows grazing grass or grass plus legume swards. It is important to note that production results varied depending on the stage of lactation of the cow. This is likely to be associated with differences in the stage of growth of different species (Grace *et al.* 2018*b*) and nutritive characteristics of the sward in different seasons, which can result in differences in DM digestibility or DM intake (DMI) of more diverse swards compared with less diverse swards (McCarthy *et al.* 2020; Nguyen *et al.* 2022). Future research efforts should consider interactions among the stage of lactation of the cow, seasonal nutritive characteristics of the sward, and type and amount of supplementary feed as potential drivers of cow production.

Sward nutritional characteristics and composition are important factors modulating the ruminant gastrointestinal environment, which in turn influences cow production and health. Studies with small ruminants have reported anthelmintic effects of more diverse pastures compared with less diverse pastures (Marley *et al.* 2003; Grace *et al.* 2019*a*). While the mechanisms involved in decreasing the gastrointestinal parasite load of animals grazing more diverse pastures is not fully elucidated, it is hypothesised that plant secondary metabolites may play a role (Min and Hart 2003). However, there is a paucity of data on the potential of diverse swards in reducing parasite load in dairy cows. It is also suggested that diversifying the grazing sward could help mitigate some of the nutritional imbalances or antinutritional factors that can occur in cows grazing monoculture pastures. Enriquez-Hidalgo *et al.* (2014) reported that cows grazing PRG plus white clover, as opposed to PRG alone in autumn increased mean ruminal pH (6.16 vs 6.00), and decreased time below ruminal pH of 6 (357 vs 704 min/22 h) and concentration of D-lactic acid (4.7 vs 6.3 mmol/L), suggesting a reduced risk for ruminal acidosis in cows grazing a PRG plus white clover; however, another study reported that cows offered fresh-cut forb species (plantain or chicory) in the afternoon and PRG plus white clover both morning and afternoon had a lower ruminal pH in the hours post-forb feeding than did cows offered only PRG plus white clover at each feeding, despite lower daily DMI by cows in the forb treatments (Minneé *et al.* 2017). Additional studies have reported that ingestive and ruminating behaviour, DM digestibility and ruminal microbial communities are dependent on sward type (Gregorini *et al.* 2013; McCarthy *et al.* 2020; Smith *et al.* 2020). Therefore, the combination of species included in the sward requires further consideration before nutritional recommendations can be made to mitigate animal health risks associated with digestive disturbances.

An area that has gained attention in recent years is the potential for diversifying the grazing sward to mitigate the environmental footprint of dairy farming. The N-fixing properties of legume forage species and their role in reducing N_2O emissions as well as the need for inorganic N application is well understood and has been discussed earlier in this review (Jensen *et al.* 2012; Cummins *et al.* 2021). In addition, inclusion of forb species and legumes in the sward can contribute to improvements in N-use efficiency and lowering N leaching to the environment relative to PRG–clover pastures (Beukes *et al.* 2014; Rawnsley *et al.* 2019). For example, Woods *et al.* (2018) reported that after application of urine from cows grazing an Italian ryegrass–plantain–white clover sward or a PRG–white clover back to each respective sward, urine N leaching was reduced by 88.9% in the more diverse sward compared with the least diverse sward. Other studies have reported on the ruminal methane-mitigation potential of multispecies swards for dairy cows associated with plant secondary metabolites (e.g. tannins; Loza *et al.* 2021*a*) and nutritive characteristics of the sward (Jonker *et al.* 2019; Loza *et al.* 2021*b*), but results have been inconclusive. However, the relative contribution of multispecies swards to mitigating undesirable environmental outcomes is likely to be determined by the type and density of species in the sward and environmental conditions (e.g. soil type, temperature, rain patterns, etc.). Further, evaluations at a system level are required to account for soil, plant and animal interactions across seasons that ultimately determine the productivity, environmental footprint, and profitability of dairy farms (Unkovich 2012; Bryant *et al.* 2020).

Conclusions

The present review has sought to identify research gaps, challenges and opportunities associated with multispecies swards and their potential to enhance the Australian dairy feedbase. International interest in this topic has intensified in the past 5 years, with several new studies being published covering a variety of aspects of multispecies swards from soil to plant to animal. These studies have highlighted the potential benefits of multispecies swards such as equal or even increased productivity in low N-input multispecies swards compared against high N-input PRG monocultures. The literature also suggests that multispecies swards can be persistent through summer drought, resilient to grazing if managed appropriately, and a source of high-quality feed for ruminants. Through the ability to reduce inorganic-N inputs, multispecies swards have been shown to reduce nitrous oxide emissions and increase N-use efficiency of systems, while also having positive effects on soil fertility in the longer term (~10 years). Although only a few studies have specifically tested milk productivity and animal-health effects of grazing ruminants consuming multispecies swards, initial results are encouraging. However, studies have often reported that mixtures did not exhibit these potential benefits consistently, perhaps due to different seed-mixture designs, eventual botanical composition, environment effects, or interactions with management systems. Identified challenges associated with multispecies swards centred around the complexity of options they offer. From seed-mixture design, the eventual botanical composition, functional group choice and proportion, species richness, and ongoing management, no two multispecies swards will ever be identical. There remains uncertainty around what is the best way to approach the above-mentioned aspects of multispecies sward implementation for best effect and it can be expected that there will not be a 'one size fits all' solution. There were examples in the literature of studies where multispecies swards required early renovation to rectify species loss, were less nutritious than a PRG control, or did not yield as well as expected under grazing, showing that greater understanding of the mechanisms that drive successful multispecies swards is needed. The potential benefits and identified challenges are summarised in Fig. 3.

Topics where further Australian-specific research would be beneficial include (1) a greater understanding on how to design the species mixture according to the target use-case and environment, (2) longer-term studies (5+ years) to understand effects on soil function, persistency of species and the sward as a whole, with a focus on rotational grazing scenarios, (3) optimal sward management and how this interacts with changes to botanical composition of the sward to guarantee that a multispecies sward reaches its full production potential, (4) a greater focus on animal studies to understand the effect of consuming different multispecies swards on production and health responses of lactating cows as well as a feed source to support dairy youngstock, and dry dairy cows, and (5) the potential of multispecies swards to contribute to mitigation of methane and N_2O emissions. Due to an overwhelming number of possible multispecies sward designs, advanced modelling methods may be useful to test a greater number of options than can subsequently be measured in physical studies, and to extrapolate the impact of findings. In conclusion, although there is still much to understand about the mechanisms governing what makes a multispecies sward successful, the mounting evidence that diverse pastures can be environmentally

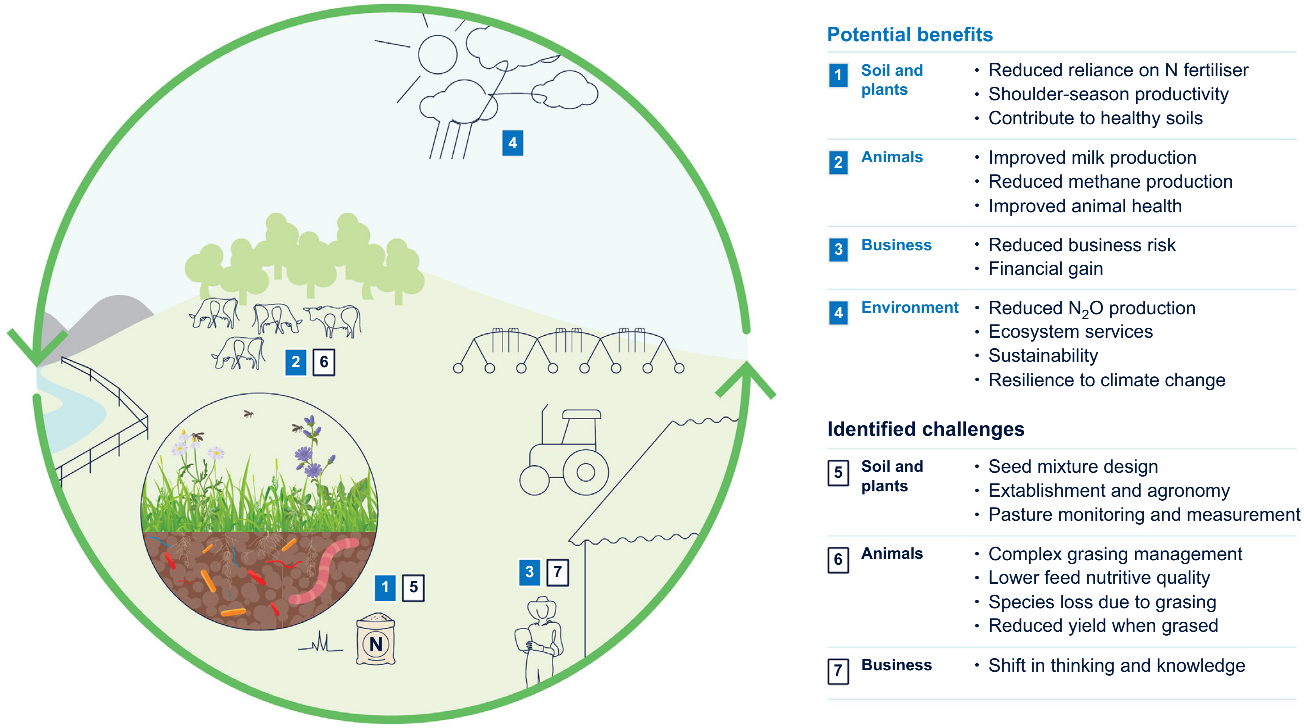

Fig. 3. A summary of potential benefits and identified challenges concerning the adoption of multispecies swards in farming systems.

positive, resilient to future climate scenarios, and adequately productive and nutritious, compared against intensive monoculture grasslands, suggests that they will have a positive impact if adopted by Australian dairy farmers. The greatest challenge to their adoption will likely be in providing optimal advice to producers, as they depart from traditional methods, to help them navigate the potential complexities of this alternative approach.

References

Baker S, Lynch MB, Godwin F, Boland TM, Kelly AK, Evans ACO, Murphy PNC, Sheridan H (2023) Multispecies swards outperform perennial ryegrass under intensive beef grazing. *Agriculture, Ecosystems & Environment* **345**, 108335. doi:10.1016/j.agee.2022.108335

Barker ZE, Thomson A, Humphries DJ, Jones HE, Misselbrook T, Beaumont D, Lukac M, Wu L, Reynolds CK (2021) Annual biomass yield and composition of three multi-species forage mixtures compared with perennial ryegrass. In 'Proceedings of the 13th BGS Research Conference', 2nd – 4 March 2021. (British Grassland Society)

Beukes PC, Gregorini P, Romera AJ, Woodward SL, Khaembah EN, Chapman DF, Nobilly F, Bryant RH, Edwards GR, Clark DA (2014) The potential of diverse pastures to reduce nitrogen leaching on New Zealand dairy farms. *Animal Production Science* **54**, 1971–1979. doi:10.1071/AN14563

Black AD, Laidlaw AS, Moot DJ, O'Kiely P (2009) Comparative growth and management of white and red clovers. *Irish Journal of Agricultural and Food Research* **48**, 149–166.

Bolland MDA, Russell WK (2010) Changes in chemical properties of 48 intensively grazed, rain-fed dairy paddocks on sandy soils over 11 years of liming in south-western Australia. *Soil Research* **48**, 682–692. doi:10.1071/SR09199

Bracken CJ, Lanigan GJ, Richards KG, Müller C, Tracy SR, Grant J, Krol DJ, Sheridan H, Lynch MB, Grace C, Fritch R, Murphy PNC (2020) Sward composition and soil moisture conditions affect nitrous oxide emissions and soil nitrogen dynamics following urea-nitrogen application. *Science of The Total Environment* **722**, 137780. doi:10.1016/j.scitotenv.2020.137780

Bracken CJ, Lanigan GJ, Richards KG, Müller C, Tracy SR, Murphy PNC (2022) Seasonal effects reveal potential mitigation strategies to reduce N2O emission and N leaching from grassland swards of differing composition (grass monoculture, grass/clover and multispecies). *Agriculture, Ecosystems & Environment* **340**, 108187. doi:10.1016/j.agee.2022.108187

Brennan RF, Penrose B, Bell RW (2019) Micronutrients limiting pasture production in Australia. *Crop and Pasture Science* **70**, 1053–1064. doi:10.1071/CP19087

Bryant RH, Miller ME, Greenwood SL, Edwards GR (2017) Milk yield and nitrogen excretion of dairy cows grazing binary and multispecies pastures. *Grass and Forage Science* **72**, 806–817. doi:10.1111/gfs.12274

Bryant RH, Snow VO, Shorten PR, Welten BG (2020) Can alternative forages substantially reduce N leaching? Findings from a review and associated modelling. *New Zealand Journal of Agricultural Research* **63**, 3–28. doi:10.1080/00288233.2019.1680395

Chapagain T, Lee EA, Raizada MN (2020) The potential of multi-species mixtures to diversify cover crop benefits. *Sustainability* **12**, 2058. doi:10.3390/su12052058

Chapman DF, Tharmaraj J, Nie ZN (2008) Milk-production potential of different sward types in a temperate southern Australian environment. *Grass and Forage Science* **63**, 221–233. doi:10.1111/j.1365-2494.2008.00627.x

Collins RP, Delagarde R, Hussey S (2014) Biomass production in multispecies and grass monoculture swards under cutting and rotational grazing. In 'Proceedings of the 25th General Meeting of the European Grassland Federation'. (Institute of Biological, Environmental and Rural Sciences (IBERS))

Cummins S, Finn JA, Richards KG, Lanigan GJ, Grange G, Brophy C, Cardenas LM, Misselbrook TH, Reynolds CK, Krol DJ (2021) Beneficial effects of multi-species mixtures on N2O emissions from intensively managed grassland swards. *Science of The Total Environment* **792**, 148163. doi:10.1016/j.scitotenv.2021.148163

Dairy Australia (2019) Feed and animal nutrition survey report. Dairy Australia, Southbank, Australia.

Darch T, Blackwell MSA, Hood J, Lee MRF, Storkey J, Beaumont DA, McGrath SP (2022) The effect of soil type on yield and micronutrient content of pasture species. *PLoS ONE* **17**, e0277091. doi:10.1371/journal.pone.0277091

des Roseaux MD, Shi S, Duff AM, Brennan FP, Condron L, Finn JA, Richards KG, O'Callaghan M, Clough TJ (2022) Impacts of pasture species and ruminant urine on N_2O emissions and nitrogen transforming microbial communities in soil mesocosms. *New Zealand Journal of Agricultural Research* **65**, 42–62. doi:10.1080/00288233.2020.1848880

Dodd M, Dalley D, Wims C, Elliott D, Griffin A (2019) A comparison of temperate pasture species mixtures selected to increase dairy cow production and reduce urinary nitrogen excretion. *New Zealand Journal of Agricultural Research* **62**, 504–527. doi:10.1080/00288233.2018.1518246

Döring TF, Baddeley JA, Brown R, Collins R, Crowley O, Cuttle S, Howlett SA, Jones HE, McCalman H, Measures M, Pearce BD, Pearce H, Roderick S, Stobart R, Storkey J, Tilston EL, Topp K, Watson C, Winkler LR, Wolfe MS (2013) Using legume-based mixtures to enhance the nitrogen use efficiency and economic viability of cropping systems. Final report (LK09106/HGCA3447). (HGCA) Available at https://orgprints.org/id/eprint/24662/1/PR513.pdf [Verified 8 May 2023]

Eisenhauer N, Lanoue A, Strecker T, Scheu S, Steinauer K, Thakur MP, Mommer L (2017) Root biomass and exudates link plant diversity with soil bacterial and fungal biomass. *Scientific Reports* **7**, 44641. doi:10.1038/srep44641

Enriquez-Hidalgo D, Hennessy D, Gilliland T, Egan M, Mee JF, Lewis E (2014) Effect of rotationally grazing perennial ryegrass white clover or perennial ryegrass only swards on dairy cow feeding behaviour, rumen characteristics and sward depletion patterns. *Livestock Science* **169**, 48–62. doi:10.1016/j.livsci.2014.09.002

FAO (2016) The global dairy sector: facts. Available at https://www.fil-idf.org/wp-content/uploads/2016/12/FAO-Global-Facts-1.pdf [Verified 25 November 2022]

Finn JA, Kirwan L, Connolly J, Sebastia MT, Helgadottir A, Baadshaug OH, Belanger G, Black A, Brophy C, Collins RP, Cop J, Dalmannsdottir S, Delgado I, Elgersma A, Fothergill M, Frankow-Lindberg BE, Ghesquiere A, Golinska B, Golinski P, Grieu P, Gustavsson A-M, Hoglind M, Huguenin-Elie O, Jorgensen M, Kadziuliene Z, Kurki P, Llurba R, Lunnan T, Porqueddu C, Suter M, Thumm U, Lüscher A (2013) Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: a 3-year continental-scale field experiment. *Journal of Applied Ecology* **50**, 365–375. doi:10.1111/1365-2664.12041

Frame J, Newbould P (1986) Agronomy of white clover. In 'Advances in agronomy'. (Ed. NC Brady) pp. 1–88. (Academic Press)

Grace C, Boland T, Sheridan H, Kirwan L, Fritch R, Lynch M (2018*a*) Effect of nitrogen on the production of multispecies swards compared to perennial ryegrass only swards. In 'Grassland science in Europe. Vol. 23', pp 200–202. (European Grassland Federation)

Grace C, Boland TM, Sheridan H, Lott S, Brennan E, Fritch R, Lynch MB (2018*b*) The effect of increasing pasture species on herbage production, chemical composition and utilization under intensive sheep grazing. *Grass and Forage Science* **73**, 852–864. doi:10.1111/gfs.12379

Grace C, Lynch MB, Sheridan H, Lott S, Fritch R, Boland TM (2019*a*) Grazing multispecies swards improves ewe and lamb performance. *Animal* **13**, 1721–1729. doi:10.1017/S1751731118003245

Grace C, Boland TM, Sheridan H, Brennan E, Fritch R, Lynch MB (2019*b*) The effect of grazing versus cutting on dry matter production of multispecies and perennial ryegrass-only swards. *Grass and Forage Science* **74**, 437–449. doi:10.1111/gfs.12440

Gregorini P, Minnee EMK, Griffiths W, Lee JM (2013) Dairy cows increase ingestive mastication and reduce ruminative chewing when grazing chicory and plantain. *Journal of Dairy Science* **96**, 7798–7805. doi:10.3168/jds.2013-6953

Hamilton LJ, Reed KFM, Leach EMA, Brockwell J (2015) Boron deficiency in pasture based on subterranean clover (*Trifolium subterraneum* L.) is linked to symbiotic malfunction. *Crop and Pasture Science* **66**, 1197–1212. doi:10.1071/CP14300

Hearn C, Egan M, Lynch MB, Fleming C, O'Donovan M (2022) Seasonal variations in nutritive and botanical composition properties of multispecies grazing swards over an entire dairy grazing season. *Grassland Research* **1**, 221–233. doi:10.1002/glr2.12037

Hector A, Schmid B, Beierkuhnlein C, Caldeira MC, Diemer M, Dimitrakopoulos PG, Finn JA, Freitas H, Giller PS, Good J, Harris R, Högberg P, Huss-Danell K, Joshi J, Jumpponen A, Körner C, Leadley PW, Loreau M, Minns A, Mulder CPH, O'Donovan G, Otway SJ, Pereira JS, Prinz A, Read DJ, Scherer-Lorenzen M, Schulze E-D, Siamantziouras A-SD, Spehn EM, Terry AC, Troumbis AY, Woodward FI, Yachi S, Lawton JH (1999) Plant diversity and productivity experiments in European grasslands. *Science* **286**, 1123–1127. doi:10.1126/science.286.5442.1123

Hill JO, Simpson RJ, Wood JT, Moore AD, Chapman DF (2005) The phosphorus and nitrogen requirements of temperate pasture species and their influence on grassland botanical composition. *Australian Journal of Agricultural Research* **56**, 1027–1039. doi:10.1071/AR04279

Hoekstra NJ, Suter M, Finn JA, Husse S, Lüscher A (2015) Do belowground vertical niche differences between deep- and shallow-rooted species enhance resource uptake and drought resistance in grassland mixtures?. *Plant and Soil* **394**, 21–34. doi:10.1007/s11104-014-2352-x

Humphreys J, Mihailescu E, Casey IA (2012) An economic comparison of systems of dairy production based on N-fertilized grass and grass–white clover grassland in a moist maritime environment. *Grass and Forage Science* **67**, 519–525. doi:10.1111/j.1365-2494.2012.00871.x

Humphreys J, Phelan P, Li LD, Burchill W, Eriksen J, Casey I, Enríquez-Hidalgo D, Søegaard K (2017) White clover supported pasture-based systems in north-west Europe. In 'Legumes in cropping systems'. (Eds D Murphy-Bokern, FL Stoddard, CA Watson) pp. 139–156. (CABI: Wallingford, UK)

Huyghe C, Litrico I, Surault F (2012) Agronomic value and provisioning services of multi-species swards. *Grassland Science in Europe* **17**, 35–46

Jaramillo DM, Sheridan H, Soder K, Dubeux JCB Jr (2021) Enhancing the sustainability of temperate pasture systems through more diverse swards. *Agronomy* **11**, 1912. doi:10.3390/agronomy11101912

Jensen ES, Peoples MB, Boddey RM, Gresshoff PM, Hauggaard-Nielsen H, Alves BJR, Morrison MJ (2012) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* **32**, 329–364. doi:10.1007/s13593-011-0056-7

Jing J, Søegaard K, Cong W-F, Eriksen J (2017) Species diversity effects on productivity, persistence and quality of multispecies swards in a four-year experiment. *PLoS ONE* **12**, e0169208. doi:10.1371/journal.pone.0169208

Jonker A, Farrell L, Scobie D, Dynes R, Edwards G, Hague H, McAuliffe R, Taylor A, Knight T, Waghorn G (2019) Methane and carbon dioxide emissions from lactating dairy cows grazing mature ryegrass/white clover or a diverse pasture comprising ryegrass, legumes and herbs. *Animal Production Science* **59**, 1063–1069. doi:10.1071/AN18019

Jordon MW, Willis KJ, Bürkner P-C, Petrokofsky G (2022) Rotational grazing and multispecies herbal leys increase productivity in temperate pastoral systems – a meta-analysis. *Agriculture, Ecosystems & Environment* **337**, 108075. doi:10.1016/j.agee.2022.108075

Jordon MW, Winter DM, Petrokofsky G (2023) Advantages, disadvantages, and reasons for non-adoption of rotational grazing, herbal leys, trees on farms and ley-arable rotations on English livestock farms. *Agroecology and Sustainable Food Systems* **47**, 330–354. doi:10.1080/21683565.2022.2146253

Komainda M, Muto P, Isselstein J (2022) Interaction of multispecies sward composition and harvesting management on herbage yield and quality from establishment phase to the subsequent crop. *Grass and Forage Science* **77**, 89–99. doi:10.1111/gfs.12554

Lange M, Eisenhauer N, Sierra CA, Bessler H, Engels C, Griffiths RI, Mellado-Vázquez PG, Malik AA, Roy J, Scheu S, Steinbeiss S, Thomson BC, Trumbore SE, Gleixner G (2015) Plant diversity increases soil microbial activity and soil carbon storage. *Nature Communications* **6**, 6707. doi:10.1038/ncomms7707

Lee MRF, Theobald VJ, Gordon N, Leyland M, Tweed JKS, Fychan R, Scollan ND (2014) The effect of high polyphenol oxidase grass silage on metabolism of polyunsaturated fatty acids and nitrogen across the rumen of beef steers. *Journal of Animal Science* **92**, 5076–5087. doi:10.2527/jas.2014-7812

Loges R, Loza C, Voss P, Kluß C, Malisch C, Taube F (2020) The potential of multispecies swards for eco-efficient dairy production in Northern Germany. In 'Proceedings of the Grassland Science in Europe', 19–22 October 2020, Helsinki, Finland. pp. 312–314. (Natural Resources Institute: Helsinki, Finland)

Loza C, Verma S, Wolffram S, Susenbeth A, Blank R, Taube F, Loges R, Hasler M, Kluß C, Malisch CS (2021*a*) Assessing the potential of diverse forage mixtures to reduce enteric methane emissions *in vitro*. *Animals* **11**, 1126. doi:10.3390/ani11041126

Loza C, Reinsch T, Loges R, Taube F, Gere JI, Kluß C, Hasler M, Malisch CS (2021*b*) Methane emission and milk production from jersey cows grazing perennial ryegrass–white clover and multispecies forage mixtures. *Agriculture* **11**, 175. doi:10.3390/agriculture11020175

Lüscher A, Barkaoui K, Finn JA, Suter D, Suter M, Volaire F (2022) Using plant diversity to reduce vulnerability and increase drought resilience of permanent and sown productive grasslands. *Grass and Forage Science* **77**, 235–246. doi:10.1111/gfs.12578

Marley CL, Cook R, Keatinge R, Barrett J, Lampkin NH (2003) The effect of birdsfoot trefoil (*Lotus corniculatus*) and chicory (*Cichorium intybus*) on parasite intensities and performance of lambs naturally infected with helminth parasites. *Veterinary Parasitology* **112**, 147–155. doi:10.1016/S0304-4017(02)00412-0

Martínez-Dalmau J, Berbel J, Ordóñez-Fernández R (2021) Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. *Sustainability* **13**, 5625. doi:10.3390/su13105625

McCarthy KM, McAloon CG, Lynch MB, Pierce KM, Mulligan FJ (2020) Herb species inclusion in grazing swards for dairy cows: a systematic review and meta-analysis. *Journal of Dairy Science* **103**, 1416–1430. doi:10.3168/jds.2019-17078

McNally SR, Laughlin DC, Rutledge S, Dodd MB, Six J, Schipper LA (2015) Root carbon inputs under moderately diverse sward and conventional ryegrass–clover pasture: implications for soil carbon sequestration. *Plant and Soil* **392**, 289–299. doi:10.1007/s11104-015-2463-z

Min BR, Hart SP (2003) Tannins for suppression of internal parasites. *Journal of Animal Science* **81**, E102–E109.

Minneé EMK, Waghorn GC, Lee JM, Clark CEF (2017) Including chicory or plantain in a perennial ryegrass/white clover-based diet of dairy cattle in late lactation: feed intake, milk production and rumen digestion. *Animal Feed Science and Technology* **227**, 52–61. doi:10.1016/j.anifeedsci.2017.03.008

Nguyen TT, Navarrete S, Horne DJ, Donaghy DJ, Kemp PD (2022) Forage plantain (*Plantago lanceolata* L.): meta-analysis quantifying the decrease in nitrogen excretion, the increase in milk production, and the changes in milk composition of dairy cows grazing pastures containing plantain. *Animal Feed Science and Technology* **285**, 115244. doi:10.1016/j.anifeedsci.2022.115244

Nyfeler D, Huguenin-Elie O, Suter M, Frossard E, Connolly J, Lüscher A (2009) Strong mixture effects among four species in fertilized agricultural grassland led to persistent and consistent transgressive overyielding. *Journal of Applied Ecology* **46**, 683–691. doi:10.1111/j.1365-2664.2009.01653.x

Nyfeler D, Huguenin-Elie O, Suter M, Frossard E, Lüscher A (2011) Grass–legume mixtures can yield more nitrogen than legume pure stands due to mutual stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agriculture, Ecosystems & Environment* **140**, 155–163. doi:10.1016/j.agee.2010.11.022

Oenema O, de Klein C, Alfaro M (2014) Intensification of grassland and forage use: driving forces and constraints. *Crop and Pasture Science* **65**, 524–537. doi:10.1071/CP14001

Ozcan G, Ates S, Cİcek H, Isİk S, Loss SP (2015) Dry matter production, botanical composition and water use efficiency of simple and multispecies pasture mixtures. In '2nd ICSAE 2015, International Conference on Sustainable Agriculture and Environment', 30 September – 3 October 2015, Konya, Turkey. Proceedings book, vol. I & II, 2015. pp. 810–816. (Selcuk University)

Pembleton KG, Tozer KN, Edwards GR, Jacobs JL, Turner LR (2015) Simple versus diverse pastures: opportunities and challenges in dairy systems. *Animal Production Science* **55**, 893–901. doi:10.1071/AN14816

Podolyan A, Di HJ, Cameron KC (2020) Effect of plantain on nitrous oxide emissions and soil nitrification rate in pasture soil under a simulated urine patch in Canterbury, New Zealand. *Journal of Soils and Sediments* **20**, 1468–1479. doi:10.1007/s11368-019-02505-1

Rawnsley RP, Smith AP, Christie KM, Harrison MT, Eckard RJ (2019) Current and future direction of nitrogen fertiliser use in Australian grazing systems. *Crop and Pasture Science* **70**, 1034–1043. doi:10.1071/CP18566

Rogers ME, Lawson AR, Giri K, Williams Y, Garner JB, Marett LC, Wales WJ, Jacobs JL (2022) Effects of extreme summer heat events on nutritive characteristics of dairy pastures in northern Victoria, Australia. *Animal Production Science* **62**, 736–742. doi:10.1071/AN21012

Sanderson MA, Soder KJ, Muller LD, Klement KD, Skinner RH, Goslee SC (2005) Forage mixture productivity and botanical composition in pastures grazed by dairy cattle. *Agronomy Journal* **97**(5), 1465–1471. doi:10.2134/agronj2005.0032

Shepperd S, Thomson A, Beaumont D, Misselbrook T, Jones H, Reynolds C, Lukac M (2020) Forage plant mixture type interacts with soil moisture to affect soil nutrient availability in the short term. *Experimental Results* **1**, e42. doi:10.1017/exp.2020.47

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

Skinner RH, Gustine DL, Sanderson MA (2004) Growth, water relations, and nutritive value of pasture species mixtures under moisture stress. *Crop science* **44**(4), 1361–1369. doi:10.2135/cropsci2004.1361

Skinner RH, Sanderson MA, Tracy BF, Dell CJ (2006) Above- and belowground productivity and soil carbon dynamics of pasture mixtures. *Agronomy Journal* **98**, 320–326. doi:10.2134/agronj2005.0180a

Smith PE, Enriquez-Hidalgo D, Hennessy D, McCabe MS, Kenny DA, Kelly AK, Waters SM (2020) Sward type alters the relative abundance of members of the rumen microbial ecosystem in dairy cows. *Scientific Reports* **10**, 9317. doi:10.1038/s41598-020-66028-3

Suter M, Connolly J, Finn JA, Loges R, Kirwan L, Sebastia M-T, Lüscher A (2015) Nitrogen yield advantage from grass-legume mixtures is robust over a wide range of legume proportions and environmental conditions. *Global Change Biology* **21**, 2424–2438. doi:10.1111/gcb.12880

Thilakarathna MS, McElroy MS, Chapagain T, Papadopoulos YA, Raizada MN (2016) Belowground nitrogen transfer from legumes to non-legumes under managed herbaceous cropping systems. A review. *Agronomy for Sustainable Development* **36**, 58. doi:10.1007/s13593-016-0396-4

Unkovich M (2012) Nitrogen fixation in Australian dairy systems: review and prospect. *Crop and Pasture Science* **63**, 787–804. doi:10.1071/CP12180

Woods RR, Cameron KC, Edwards GR, Di HJ, Clough TJ (2018) Reducing nitrogen leaching losses in grazed dairy systems using an Italian ryegrass–plantain–white clover forage mix. *Grass and Forage Science* **73**, 878–887. doi:10.1111/gfs.12386

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. This research did not receive any specific funding.

Acknowledgements. The authors thank Professor Joe Jacobs of Agriculture Victoria Research, and Cath Lescun and Ruairi McDonnell of Dairy Australia for kindly offering advice and expertise to improve this review and for proofreading.

Author affiliations

[A]Agriculture Victoria Research, Ellinbank Smart Farm, 1301 Hazeldean Road, Ellinbank, Vic. 3821, Australia.

[B]Dairy Australia, Melbourne, Vic. 3006, Australia.