**Review Paper: The role of forage management in addressing challenges facing Australasian dairy farming**

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**Short title:** Review of forage management in Australasian dairy farming

**Abstract**

Forage management underpins the viability of pastoral dairy systems.  This review investigates recent developments in forage research and their potential to enable pastoral dairy systems to meet the challenges that will be faced over the next 10 years.  Grazing management, complementary forages, pasture diversity, fertiliser use, chemical restriction, irrigation management and pasture breeding are considered. None of these areas of research are looking to increase production directly through increased inputs but rather they aim to lift maximum potential production, defend against production decline or improve the efficiency of the resource base and inputs.   Technology approaches consistently focus on improving efficiency while genetic improvement or the use of complementary forages and species diversity aim to lift production. These approaches do not require additional labour to implement, but many will require an increase in skill level. Only a few areas will help address animal welfare (e.g. the use of selected complementary forages and novel endophytes) and only complementary forages will help address increased competition from non-dairy alternatives by positively influencing the properties of milk.  Overall, the diversity of activity and potential effects will provide managers of pastoral dairy systems with the best tools to respond to the production and environmental challenges they face over the next 10 years.

**Additional keywords:** Feedbase, pasture, intensive grazing, alternative forages, fertiliser, system efficiencies

**Introduction**

Farms that feed dairy cows with directly grazable forage year round in Australia and New Zealand have a comparative advantage over farms in regions where, due to climate constraints, cows are housed indoors for part or all of the year (Dillon *et al.* 2005).  To maintain this comparative advantage, considerable research effort has focused on increasing the production and direct consumption of forage. While maintaining forage production and consumption will continue to be a challenge, especially under a changing climate, other challenges are emerging in terms of environmental impact, labour (supply and skills), animal welfare, and competition with non-animal alternatives to dairy.

Past research on forage management has focused on improved management and greater inputs to the existing forages (Rawnsley *et al.* 2014; McCarthy *et al.* 2014), genetic improvement of  forages (Lee *et al.* 2012; Harmer *et al.* 2016), integration of high yielding forage crops (Garcia *et al.* 2008; Tharmaraj *et al.* 2014) and the use of complementary perennial forage species (Pembleton *et al.* 2015b, 2016; Lee *et al.* 2015). The impact of this research has primarily been on productivity (usually in a combination of both production/ha and production/cow), but the manner in which productivity gains have been achieved is different.  There has also likely been effects (both positive and negative) on the other challenges (environmental impacts, labour requirements, animal welfare) faced by the industry, however, these often are not assessed/considered alongside productivity.

Improvements to agricultural productivity can be understood within a ‘production frontier’ framework proposed by Keating *et al.* (2010), which has been partly applied to understand the opportunities for improving Australian pastoral industries (Bell *et al.* 2014).  This framework can be used to understand how forage management interventions change the system state in relation to forage production and consumption (Fig 1a).  For example increasing inputs such as fertiliser, irrigation or management effort (e.g. more sophisticated grazing management) moves production along a response frontier from A to B.  Concurrent with this, the effect on the input loss frontier (as a way of conceptualising the environmental impact; Fig 1b) also moves from A to B. It may not be profitable for the system to continue to use inputs to increase production due to diminishing returns, particularly if input losses are increasing at a greater rate (B to C in both Fig 1a and b).  Successfully integrating a new cultivar or a complementary species may lift the production potential and hence place the system on a new production frontier (B to D, Fig1a). This also increases the ability of the system to better utilise additional inputs and hence shifts the input loss frontier (B to D, Fig 1b). There are risks associated with a change in the system and the failed integration of a new forage or the selection of a poorly-adapted cultivar resulting in a reduction of the production frontier (B to E, Fig 1a). The application of new technology to make more efficient use of inputs also changes both the production and input loss frontiers. While the technology itself cannot increase the maximum system production or the maximum amount of inputs it can fully utilise, it changes the production frontier so that production is achieved with less inputs (B to F, Fig 1a), or the same level of input use can be maintained with less losses (B to F, Fig 1b).  Failure to respond to system degradation either from internal (e.g. weed/pest incursion) or external (e.g. changing climate) sources will result in reducing the production frontier (B to E, Fig 1a) and increase input losses (B to E, Fig 1b).

Modifying the production frontier, particularly through the use of technology or a major change in forage species, will increase the skill level required from the farm labour.  This potentially creates challenges in terms of accessing and financing these skills which can limit the change in the production frontier. Overlaying these frameworks are challenges posed by animal welfare and increasing demand from some market segments for alternatives to dairy products.

In the remainder of this paper we examine how specific aspects of dairy forage research effect the production and input loss frontiers, with the intention of identifying if and how forage research can address the challenges facing pastoral dairy systems over the next 10 years.

\*Insert Figure 1 here

**Grazing management**

The predominant forage base in pastoral dairy industries are mixed swards of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.).  These species  establish easily, have well-defined grazing management regimes and are directly grazable (Rawnsley *et al.* 2013).  The underlying principle of grazing management is to optimise the quantity and nutritive value of forage consumed, through understanding plant physiological response to defoliation (Fulkerson and Donaghy 2001; Roche *et al*. 2017), and hence move the system along the production frontier.  It is widely accepted that in ryegrass pastures, persistence, production and nutritive value are optimised with a grazing rotation that allows development of between 2 and 3 leaves per tiller (the 2- to 3-leaf regrowth stage), and a post-grazing residual between 40 to 50 mm (Rawnsley *et al.* 2014; Pembleton *et al.* 2017).

 Pasture persistence is becoming increasingly challenged under a changing and more variable climate (Nie and Norton 2009) and is threatening to degrade the production and input loss frontier, particularly in marginal areas. Rawnsley *et al.* (2014) identified that irrespective of input management (water or nitrogen), within 18 months pastures defoliated at the 2-leaf or 3-leaf regrowth stage had 30-40% greater tiller density than pastures defoliated at the 1-leaf regrowth stage. Similarly, defoliation to a height of 30mm resulted in a 30% decline in tiller density compared to defoliating to 55mm. With both pasture production and persistence challenged by a changing climate, any deviation from the correct application of grazing principles will lower the farm’s production frontier.

 McCarthy *et al*. (2014) highlighted the potential to increase on-farm productivity through better grazing management practices. This survey identified that 49% of paddocks were grazed too soon based on leaf stage, 62% were grazed outside the recommended pre-grazing biomass, and 48% were not grazed to an appropriate post-grazing biomass.  While it is not possible to identify the direct cause of this, it is postulated that it is at least in part due to conflicting labour demands on farm. Grazing management decisions commonly occur twice daily on most dairy farms where cows are milked morning and evening. Therefore, significant scope exists to improve the production frontier by getting these key grazing decisions correct more often. Effective grazing management requires decision making in the context of future events (e.g. the pasture will be at the 3-leaf regrowth stage in seven days’ time) rather than reacting to descriptive measures of the present moment (e.g. the pasture is at the 3-leaf regrowth stage today) (Macdonald *et al.* 2010). This has led to a focus on providing predictions of leaf appearance and pasture growth rates, to inform grazing management decisions and hence improve efficiency.

Leaf appearance rate for ryegrass remains constant when light and temperature conditions are constant (Mitchell 1953).  Consequently, simple and accurate predictive algorithms for leaf appearance rate can be developed (Johnson *et al.* 2007; Barrett *et al.* 2005).  While these predictive algorithms can be applied to determine leaf appearance rate, pasture growth rate and pasture on offer are as equally important.  The use of pasture forecasting is gaining increasing attention as the predictive capability can be embedded into a cloud computing environment, bringing together the capacity to ingest data and deliver predictions to grazing managers in real-time.  Harrison *et al*. (2017) reported on a cloud-based system to ingest real-time *in-situ* sensor data and regional climate data fused with a pasture growth model to deliver pasture growth estimates via a web-interface. The outcome is better grazing management decisions. Successful weather forecasting was a key determinant in the accuracy of the growth forecast, indicating that developments in fields considered outside of the scope of pasture research will be critical to the application of technology to improve grazing management.

There is little doubt that our knowledge of pasture physiology has contributed to the development of grazing management practices that have underpinned the success of pastoral dairy systems (Roche *et al.* 2017) via movement along the production frontier.  However, this has in part created other challenges with respect to increased stocking rates and environmental impacts (particularly nitrate leaching). Leaching of nitrate nitrogen (N) from urine and dung patches to ground and surface water leading to eutrophication of water bodies is an environmental concern particularly in New Zealand (Marsh, 2012). Reducing the N consumed is considered an effective means of reducing urinary N losses in grazed systems (Dijkstra *et al.* 2013). Leaf regrowth stage has been shown to influence the crude protein (CP) concentration of perennial ryegrass, with pasture crude protein concentration reducing proportionally by 11-15% as each new leaf emerges from the 1-leaf to the 3-leaf stage (Fulkerson and Donaghy 2001; Pembleton *et al.* 2017). Similarly, Bryant *et al.* (2012) showed that delaying grazing from the morning to the afternoon and extending the growth from the second to the fourth leaf stage achieved a threefold increase in the water-soluble carbohydrate to CP ratio of perennial ryegrass. Pembleton *et al*. (2017) suggested that grazing at the 3 leaf stage as opposed to more frequently will reduce N lost to the environment, however few grazing experiments have validated this.  Bryant *et al.* (2014) reported that although reductions in herbage N concentration were achieved by increasing the regrowth interval, mid-spring milk production was compromised with little gain in N use efficiency. Clearly, while grazing management is critically important to optimise yield, persistence and nutritive value, the ability to address nitrate leaching and hence move the farm down the input loss frontier will not be provided through grazing management alone.

Virtual fencing technology offers much potential in the way we manage grazing animals in pastoral dairy systems. Productivity improvements are thought to be achieved by better matching grazing livestock nutritional demand with pasture availability or reducing farm labour requirements for tasks associated with livestock movement.  Whilst the required associative learning in cattle required for such systems has been demonstrated (Lee *et al*. 2009), there is still much research required to demonstrate the application of virtual fencing in pastoral dairy systems. Verdon (2018) concluded that intensifying a grazing regime is dependent on supporting the natural ingestive, digestive, and social behaviours of cattle, rather than requiring a substantial behavioural change. Whilst the technology is exciting in its potential to shift the production frontier through more sophisticated grazing management, further research is required to prove its application.

**Complementary forage species**

During summer or winter, the growth and nutritive value of perennial ryegrass can be limited by ambient temperatures or the soil water content (Rawnsley *et al.* 2013). Complementary forages can reduce the resulting feed gaps by shifting the forage production curve with the use of summer active perennial pastures (Lee *et al.* 2015). Double or triple cropping of annual forage species can be used to balance the forage supply curve (Garcia *et al.* 2008; Tharmaraj *et al.* 2014). Consistent forage deficits can be filled with high yielding single graze crops such as forage brassicas, fodder beet (*Beta vulgaris* L.) (Gibbs and Saldias 2014; Crystal *et al.* 2012) or whole crop silage (Pembleton and Rawnsley 2012; Jacobs *et al.* 2009).Thus complementary forages can help defend the production frontier from degradation (Nie *et al*. 2008).

Past research efforts have largely been successful in identifying strategies to fill forage deficits.  However, broad industry application of such practices (with the exception of the use of dedicated winter forage crops) has been limited (Rawnsley *et al*. 2013).  The establishment of annual forage crops means pasture area that has been cultivated for cropping requires replanting to perennial pasture resulting in significant periods of time when land is unavailable for grazing.  In rainfed systems this is exacerbated as feeding of the crop is concluded during periods (late summer or winter) which are not conductive to the establishment of pasture. This increases grazing pressure on the remainder of the grazing area (Tharmaraj *et al.* 2014) often resulting in negligible improvement to the production frontier.

Complementary forage species create other challenges as their best management practices often do not align with perennial ryegrass, and often management requirements between species conflict (e.g. Lee *et al.* 2015).  This increases the skill set and management effort to manage them within the pasture platform.  While the successful use of complementary forage species has presented challenges, the dedicated crop for overwintering cattle is a successful example (Gibbs and Saldias 2014).  This practice is similar to the triple cropping systems investigated by Garcia *et al.* (2008) where a section of the farm is dedicated to continuous irrigated cropping.  Rawnsley *et al*. (2013) suggests such systems can be  highly profitable, particularly in areas where land is limited.  Successful integration of annual forages occurs where the potential negative interactions with the other components of the farm system are limited through separation of the crop from the pasture platform. However, N leaching attributed to intensive winter crop grazing contributes a disportionately large fraction of whole-farm N leaching (Crystal *et al.* 2012) and hence negatively effects the input loss frontier.  Therefore the future of intensive crop grazing may be challenged where N leaching is regulated.

   A challenge still exists for the successful inclusion of perennial complementary forages into the pastoral dairy systems as the need for repeated grazing means it is difficult to isolate them from other system components.  However, recent work on fescue (*Festuca arundinacea* Schreb.; Lawson *et al.* 2017) and lucerne (*Medicago sativa* L.; Moot 2014) has identified that grazing management of these species might not be as strict as previously proposed.  Therefore, these species may be able to be managed in line with the principles of ryegrass grazing management, in which case the benefits of complementary forages could be achieved without the need for additional labour or skills.

While the majority of research on complementary species has focused on forage deficits or lifting overall production, some research has investigated their potential to address other challenges. Plantain (*Plantago lanceolata* L.), unlike many other perennial forage species, has a negative dietary cation-anion difference (DCAD; Pembleton *et al.* 2015a).  Low DCAD diets prior to calving reduce the incidence of milk fever (a major animal health challenge for pastoral dairy systems; Roche *et al*. 2008).  Therefore, plantain may provide an alternative to dusting forages with magnesium oxide or feeding specialty supplement pellets to pre-calving dairy cows.  Preliminary research evaluating this practice is encouraging (Hill 2014).

The use of complementary forages also helps mitigate the environmental effects from pastoral dairy systems by altering the input loss frontier.  Feeding species containing a high level of condensed tannins reduces methane emissions from cattle and changes the partitioning of dietary N between dung and urine (Min *et al.* 2003).  However, the productivity of these species (namely *Lotus* spp.) is below that required in pastoral dairy systems so their use lowers the production frontier. Recent evidence suggests feeding brassica species to cattle can reduce methane emissions (Sun *et al.* 2016), with the size of the effect linearly correlated with the dietary proportion of brassica. Plantain has been found to change urination behaviour, rumen ammonia production and N partitioning in a way that reduces the N loading of urine patches and leaching on dairy farms (Totty *et al.* 2013; Navarrete *et al.* 2016). Preliminary data suggest an inclusion of 20-70% plantain in the diet of dairy cows will reduce N leaching (P. Kemp pers comm). Complementary forage species also present an opportunity to intercept urinary N in the soil prior to leaching.  The use of Italian ryegrass (*Lolium multiflorum* Lam.) and oats (*Avena sativa* L.) appears to be effective in capturing urinary N (Malcolm *et al*. 2014). If grazing these swards, careful consideration will be required to ensure that this does not create grazing management challenges due to an oversupply of spring forage. Alternatively, harvesting these species for silage will capture urinary N without resulting in an oversupply of spring forage (Eriksen *et al*. 2015).

The effect that complementary forages have on the properties of derivative dairy products has received some attention with potentially positive (Muir *et al.* 2014) implications identified.  However, the translation of these effects into improving consumer preferences for dairy products on a broad scale is limited for now as industry focus is on producing globally traded commodities.

**Diverse pastures**

The inclusion of additional species directly into ryegrass-based pastures has gained recent research attention to achieve “over yielding” (Marquard *et al.* 2009) and capture the benefits of complementary species (outlined above).  If successful this will lift the production frontier of the system and depending on the additional species, improve the input loss frontier.  While benefits to forage production, nutritive value and milk production have been demonstrated (Pembleton *et al.* 2016a; Totty *et al*. 2013) these improvements are due to the individual additional species rather than an increase in species diversity (Pembleton *et al.* 2015b).  This presents a challenge to the use of more diverse pastures in pastoral dairy systems, in terms of the selection of the additional species that will be included.  Past research has often created diversity by sowing a large number (>5) of species. Often many of these species are quickly out-competed in the mixture and hence do not provided any “functional” diversity.  This not only wastes resources but potentially means that some beneficial species provide no benefit to production. The inclusion of carefully selected additional species would prevent such an outcome. However, this is likely to be highly situation specific and there is limited guidance as to how these species can be identified.

The establishment and management of mixtures also presents challenges that lower the production frontier.  The increase in diversity increases competition for limited resources of light, water and nutrients. Hence, pasture management needs to balance this competition to avoid progressing to a homogeneous sward based on natural competition. In more extensive grazing systems, the physical separation of species though spatial or alternate row planting has been used to help manage this competition (Hayes et al. 2017).  However, an examination of niche exploitation by diverse mixtures in dairy pastures identified niche exploitation is temporal rather than spatial (McLaren and Pembleton 2015). Management of diverse mixtures is often considered more complex than simpler binary mixtures due to increased complexity in grazing management and pasture nutrition. Whole farm modelling has identified that production benefits (associated with increased pasture growth and more balanced nutritive profile) can be achieved when as little as 25% of the pasture platform has more than two species (Pembleton 2015). At pasture re-sowing rates of 10% per year, complementary species will only need to persist for three years. As such, less focus is required on compromising management practices to ensure long term persistence of the additional species. Consequently, increasing pasture diversity should be a relatively simple mechanism to improve the production and input loss frontiers of pastoral dairy systems without increasing the management skills required.

**Nutrient fluxes and use efficiency**

Pastoral dairy systems have intensified as milk production has increased (as discussed above). This has been achieved by importing feed and increasing total feed grown, through greater inputs of water and fertiliser (Chapman *et al.* 2008). Subsequently whole-farm nutrient surpluses are increasing, with commensurate soil nutrient build-up, and declining nutrient use efficiency (Gourley *et al*. 2012; Stott and Gourley 2016).

The proportion of dairy farmers using N fertiliser in Australia has increased from 58% in 1992 to 80% in 2012 (Stott and Gourley 2016), with N fertiliser usage around 100 kg N/ha/year for the average Australian dairy farm. In more extensive pastoral dairy systems, legumes, notably clovers, have the potential to contribute significant N inputs (>100 kg N/ha/year) (Unkovich 2012). However, increased imported feed and fertiliser has generated greater N inputs at the farm scale and a decreasing dependence on N fixation by pasture legumes.

In an Australian nutrient balance study involving 41 dairy farms, N was always in surplus (47 to 601 kg N/ha/year; Gourley *et al.* 2012). Fertiliser N and imported feed accounted for an average of 43% and 40% of total N imports, respectively, with milk production being strongly correlated with total N imported. In contrast, pasture legume contents were generally low (median 6% of total DM), with annual N fixation <50 kg N/ha in ~80% of dairy pastures.

 Although optimum soil nutrient requirements for forages are well established, opportunities remain to improve the efficiency of nutrient supply at farm level through use of nutrient budgets/balances, and monitoring of soil nutrient availability.  Such practices increase the efficiency of production and reduce nutrient loss. Key drivers for nutrient loss to both surface and groundwater, are an oversupply of nutrients and the transport of these nutrients to water bodies (Burkitt 2014). Soil nutrient concentrations are influenced by management and nutrient balances and this provides opportunities to reduce environmental impact. While environmental drivers don’t appear as strong in Australia compared to New Zealand (Stott and Gourley 2016), increased nutrient use efficiency remains a priority in order to improve the efficiency production.

Nutrient budgeting is routinely used in New Zealand, often to meet regulatory requirements via the computer model Overseer® (Wheeler *et al.* 2003). A similar standardised whole-farm nutrient mass balance approach has been advocated for Australian dairy farms (Rugoho *et al*. 2018). Input data include soil test results of management units with similar soil type, topography and management. The potential for all paddock testing (APT) to reduce soil nutrient variation and achieve optimum concentrations have been demonstrated (e.g. Cotching *et al.* 2017; Roberts *et al.* 2011; Aarons and Gourley 2015). Based on a study of 1698 paddocks, Cotching *et al.* (2017) reported that APT could result in significant cost savings for farmers. Roberts *et al.* (2011) also reported cost savings and a fourfold increase in nutrient use efficiency.

Opportunities also exist to reduce soil test variation within paddocks to reduce the incidence of nutrient “hot spots” and minimise variability in pasture production. This approach relies on the availability of more spatially-explicit data either via grid soil sampling, portable soil nutrient sensors (Smolka *et al.* 2017), visible, near and mid-infrared spectroscopy (Forrester *et al.* 2015), or hyperspectral sensors (Wigley *et al.* 2017) and also requires the ability to apply fertiliser at a variable rate. While such technology increases nutrient use efficiency, it has not yet been widely adopted on pastoral dairy farms.

**Effect of chemical use and restriction**

Over the coming decade, some of the herbicides used routinely in dairy farming will potentially become unavailable.  An example is the current controversy being debated publicly around glyphosate restriction. This began with the release of a report labelling glyphosate as a “Probable Human Carcinogen” (IARC 2015).  These conclusions have since been disputed (Williams *et al.* 2016) but the findings of an United States of America court against Monsanto in 2018 regarding whether glyphosate caused cancer has renewed calls for its ban. Should this herbicide become unavailable, weed control during seed-bed preparation for new pastures and crops would become more difficult, negatively affecting the production frontier.

The development of herbicide resistance in weeds is a global concern and the cases of most relevance to pastoral dairy systems have been the resistance of giant buttercup (*Ranunculus acris* L.) populations to MCPB and MCPA and more recently to flumetsulam (Lusk *et al.* 2015), and also the resistance of nodding thistle (*Carduus nutans* L.) populations to MCPA and 2,4-D (Harrington *et al.* 1988).  Glyphosate resistance in annual ryegrass (*Lolium rigidum* Gaud.) (Powles *et al.* 1998) and the potential for resistance to move from glyphosate-resistant ryegrass populations into pastures via pollen (Ghanizadeh *et al.* 2016), could challenge pasture re-sowing in the future.  There is a lack of suitable selective herbicides to control weeds in complex pasture mixes containing forbs, apart possibly from flumetsulam and bentazone (Gawn *et al.* 2012). In the future, farmers may be more reliant on non-chemical management techniques to control weeds and defend production gains. Spot applications of less-selective herbicides with wiper applicators (Harrington and Ghanizadeh 2017) or automated spot  spraying technology (Schmittmann and Lammers 2017) will also play an important role.

**Effect of irrigation use and restriction**

In Australia, increasing competition with other water users, climate variability, cost of irrigation water, and reduced water availability are compelling dairy farmers to adopt innovative practices and employ technology that utilises water as efficiently as possible. Climate and land use practice affect water demand and have a significant price effect. This is particularly evident in Northern Victoria, where land use practices have changed, with significant investment in perennial horticulture leading to increased water demand from a capped resource. This is increasing the demand and price for water and placing significant market pressure on dairy farmers, negatively affecting the production frontier for farms in these regions.

In New Zealand, recent national water quality regulations are now the primary driver for efficiency. Excessive irrigation applications have been linked to the leaching of nutrients from the rooting zone which then end up in groundwater systems or waterways. To minimise these effects, all irrigators are required to have an audited Farm Environment Plan through which they have to demonstrate that their irrigation systems and management are efficient. Despite this, production efficiency from efficient irrigation remains a significant incentive. For example, irrigation schemes such as Ashburton Lyndhurst in Mid-Canterbury and Amuri in North Canterbury (both 28,000 ha), recently invested considerable capital (+$100 million each) in converting from open channel to pressure pipe distribution systems. This has enabled their shareholders (who provided the capital for the modernisation) to move from set roster flood irrigation to on-demand spray systems, resulting in a 50% lift in productivity and at least a 20% gain in water savings.

Effective irrigation practices that maximise water use efficiency require a reliable water supply and well-designed, fit for purpose irrigation systems that can apply the right amount of water at the right time. They also require accurate irrigation scheduling at the sub-paddock scale to account for spatial variability and maintain optimum pasture growth. Effective management of the spatial and temporal variability in water demand is key to optimising pasture production under irrigation.  Precision irrigation is now possible with deployment of relatively low cost sensor networks (Hedley *et al.* 2012), automated water balance models, and precision control systems such as variable rate irrigation (VRI).  This step change in irrigation capability offers an opportunity for a significant improvement in irrigation efficiency.

 Looking forward the current capability gap will need to be bridged, as such there may be a need for the irrigation service industry to move to a support focus that provides the specialist skills required to fully realise the potential benefits. One of the biggest limitations to the uptake of precision technology is accurate measures of variability that best represent spatial and temporal water requirements. The two main approaches to determining water requirements involve measuring and predicting soil or plant moisture status (Jones 2004). Recent spatial measurement of soil moisture using radiometers (Sabaghy *et al.* 2018) is promising. Furthermore, pasture growth rate is a good predictor of water deficit stress, with 50% reductions in growth rates observed when soil moisture deficits drop below the refill point (J. Hills, unpublished data).  Various methods have been developed for remote sensing of pasture biomass and growth rates including satellite (Edirisinghe *et al.* 2012), drone (Von Bueren *et al.* 2014) and ground-based (Shaefer and Lamb 2016) sensors. These spatial measures of soil and plant moisture status can be autonomously uploaded to VRI control systems to apply the right amount of water, in the right place, at the right time.

 Development of user-friendly decision support systems or fully autonomous systems are required to better utilise precision irrigation technologies for improved productivity and sustainability, to reduce the need to increase the skill level required from the farm labour pool.  The VARIwise framework is an example of an autonomous system linking input data (weather, soil moisture, pasture status) with a pasture growth model to generate VRI prescription maps (McCarthy *et al.* 2010; McCarthy *et al.* 2014).  These prescription maps can be uploaded to VRI systems, removing the requirement for labour-intensive development of these prescriptions.

 The application of VRI technology has led to water savings between 9 and 26% by minimising variation in soil moisture content (Hedley *et al.* 2013). The technology has also been shown to reduce N and phosphorus loading from intensively grazed pastures to adjacent water bodies by as much as 80-85% through reducing leaching and runoff (McDowell 2017), highlighting the potential of such approaches to improve the input loss frontier.

**Plant breeding**

Plant breeding plays a pivotal role in underpinning the sustainability and profitability of pastoral dairy systems. Although optimal management and species selection are critical to realising the full potential of the farm’s production frontier, plant breeding is fundamental to ongoing incremental improvements in the base genetic potential and hence production frontier. Recently, Harmer *et al.* (2016) estimated the rate of genetic gain in Australia and New Zealand perennial ryegrass breeding to be 0.76% with similar levels (0.35 – 0.52%) observed in Europe (McDonagh *et al.* 2016). This rate is not sufficient to defend against external pressures on the production frontier due to a changing climate. Although breeding practises are beginning to transition towards more rapid, adaptive and future (target environment) orientated breeding, current phenotypic evaluation practises mean that selection decisions made at the start of the breeding cycle are a decade in the past once a potential new cultivar is released. Approaches to dramatically reduce the generation interval must be adopted to respond more rapidly to ever-evolving target environments and significantly improve the production and input loss frontiers.

Genomic selection provides the best opportunity to meet this challenge. Genomic selection utilises a prediction equation of marker trait associated effects across the genome, developed from a genotyped and phenotyped reference population to predict the phenotypic performance from genotypic information alone. The method will reduce the generation interval (as seedlings rather than mature plants are selected) and therefore increase the rate of genetic gain. Genomic selection has been successfully developed and evaluated for ryegrass in breeding programs (Pembleton *et al.* 2018; Fè *et al.* 2016) as well as for other species such as lucerne (Annicchiarico *et al*. 2015), and is predicted to at least triple the rate of genetic gain (Lin *et al.* 2016). Technological developments in phenomics, including infield controlled environments such as rainout shelters, allow prediction equations to be developed for future environmental challenges, and hence defend against a lowering of the production frontier.

The advent of genome editing in conjunction with genomic selection methods provides new opportunities to dramatically and precisely improve specific traits such as water-soluble carbohydrates and digestibility. These step changes need to be developed within a systems approach that considers all nutritive and rumen interactions, such as seasonal profiles and water-soluble carbohydrate to CP ratios. Considering the whole system ensures that these step change improvements are captured effectively to optimise the production frontier. This will also provide opportunities to improve animal welfare by ensuring that the pasture nutritive profile matches animal requirements.

Heterosis in excess of 20% (equivalent to over two decades of breeding) has been observed in ryegrass growth and persistence (Wang *et al.* 2016). However, methodologies to deliver heterosis have until recently been unobtainable in ryegrass, due to an inability to control the crossing between parental lines. Pembleton *et al.* (2015c) proposed a strategy of genotypic selection in ryegrass to restrict the diversity around the self-incompatibility loci in parental pools that results in the preferential production of F1 hybrid seed in the final commercial seed multiplication between two parental pools.

The use of ‘novel’ endophytes in pasture breeding has resulted in improved animal health through use of endophytes that do not produce alkaloids toxic to animals, but continue to produce alkaloids that protect against insect attack (Lee *et al.* 2012). New advances in characterisation and genome editing for optimal alkaloid profiles will continue to reduce the effects of alkaloid toxicity on animal health whilst defend against their degradation in the production frontier through improved host-plant pest resistance and stress tolerance.   The use of these technological advances and innovations in breeding within a whole system approach will ensure that plant breeding program contribute to lifting the production frontier over the next decade.

**Conclusions**

Through this review we have examined how forage research will contribute to addressing the major challenges facing pastoral dairy farming systems in the future, through the lens of a production and input loss frontier framework.  A common aspect of the reviewed research is that the current focus is not on aspects that will shift the system along the production and input loss frontiers, but rather, will change these frontiers or defend against degradation (Table 1).  Previous research has focussed on intensification of pastoral dairy systems, thereby placing current pastoral dairy systems high up on the production frontier (point B on Fig. 1) where there is little incentive (economically or environmentally) to continue that intensification.  Technology improvements enabling better temporal or spatial decision making around inputs and grazing management will improve frontier efficiency. However, realising these efficiency gains may require increased specialist skills. Consequently, extension, education and training will be just as critical to realising these benefits as the research itself. Changes to the species underpinning the forage base through introducing complementary forages, increasing pasture diversity or by genetic improvement, have the potential to lift production and shift input loss. These approaches also have the potential to improve the health of dairy cattle and even modify dairy products so that they are more acceptable to consumers.  Poor integration of complementary forages could result in negative effects on production if the appropriate skill set is not available to manage these changes and broader effects on the system. The use of new pasture genetics or greater species diversity does not appear to have this challenge, making these more attractive options for the future. The continual developments of endophytes and alternative approaches to chemical usage will be important to defend against declines in the production frontier due to biotic stressors and also improve consumer acceptance of dairy products (in the case of non-chemical controls) or improvements to animal health (in the case of endophytes).  This review highlights that forage management has a clear role in addressing all the challenges facing pastoral dairy systems. The diversity of approaches (and hence diversity in effects on the production and input loss frontiers) will ensure that these systems are well placed to adapt and remain competitive in the future.

\*Insert table 1 here

**References**

Aarons SR, and Gourley CJP (2015). Between and within paddock soil nutrient, chemical variability and pasture production gradients in grazed dairy pastures. *Nutrient Cycling in Agro-ecosystems* **102**, 411-430.

Annicchiarico P, Nazzicari N, Li X, Wei Y, Pecetti L, Brummer EC (2015) Accuracy of genomic selection for alfalfa biomass yield in different reference populations. *BMC Genomics* **16,**1020

Barrett PD, Laidlaw AS, Mayne CS (2005) GrazeGro: a European herbage growth model to predict pasture production in perennial ryegrass swards for decision support. *European Journal of Agronomy* ***23*(1)**, 37-56.

 Bell LW, Hayes RC, Pembleton KG, Waters CM (2014) Opportunities and challenges in Australian grasslands: pathways to achieve future sustainability and productivity imperatives. *Crop and Pasture Science* **65**, 489-507.

Burkitt LL (2014) A review of nitrogen losses due to leaching and surface runoff under intensive pasture management in Australia *Soil Research* **52**, 621-636.

Bryant RH, Gregorini P, Edwards GR (2012) Effects of N fertilisation, leaf appearance and time of day on N fractionation and chemical composition of Lolium perenne cultivars in spring. *Animal Feed Science and Technology* ***173*(3-4)**, 210-219.

Bryant RH, Dalley DE, Gibbs J, Edwards, GR (2014) Effect of grazing management on herbage protein concentration, milk production and nitrogen excretion of dairy cows in mid‐lactation. *Grass and Forage Science* ***69*(4)**, 644-654.

Chapman DF, Kenny SN, Beca D, Johnson IR (2008) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. *Agricultural Systems* **97**, 108–125.

Cotching WE, Taylor L, Findlay S, Davies P, Bennett S, Brown R (2017) Soil nutrient concentrations and farm gate nutrient balances for dairy farm management in Tasmania. *New Zealand Journal of Agricultural Research* **60(2)**, 216-221.

Crystal JM, Monaghan RM, Dalley D, Styles T (2012) Assessment of N leaching losses from six case study dairy farms using contrasting approaches to cow wintering. *Proceedings of the New Zealand Grassland Association* **74,** 51-56.

Dijkstra J, Oenema O, Van Groenigen J, Spek J, Van Vuuren A, Bannink, A (2013) Diet effects on urine composition of cattle and N 2 O emissions. *Animal* **7**, 292-302.

Dillon, P, Roche, JR, Shalloo, L, Horan, B (2005) Optimising financial return from grazing in temperate pastures. In '*Utilisation of grazed grass in temperate animal systems. Proceedings of a satellite workshop of the XX International Grassland Congress*. ' Wageningen Academic Publishing, Cork, Ireland, pp. 131 - 147.

 Edirisinghe A, Clark D, Waugh D (2012). Spatio-temporal modelling of biomass of intensively grazed perennial dairy pastures using multispectral remote sensing. *International Journal of Applied Earth Observation and Geoinformation* **16**, 5-16.

Eriksen J, Askegaard M, Rasmusse, J, Søegaard K (2015) Nitrate leaching and residual effect in dairy crop rotations with grass–clover leys as influenced by sward age, grazing, cutting and fertilizer regimes. *Agriculture, Ecosystems & Environment* **212**, 75-84.

Fè D, Ashraf BH, Pedersen MG, Janss L, Byrne S, Roulund N, Lenk I, Didion T, Asp T, Jensen CS, Jensen J (2016) Accuracy of Genomic Prediction in a Commercial Perennial Ryegrass Breeding Program. *The Plant Genome* **9,** 1-12.

Forrester ST, Janik LJ, Soriano-Disla JM, Mason S, Burkitt L, Moody P, Gourley CJP, McLaughlin MJ (2015) Use of handheld mid-infrared spectroscopy and partial least-squares regression for the prediction of the phosphorus buffering index in Australian soils. *Soil Research* **53,** 67-80.

 Fulkerson WJ, Donaghy DJ (2001) Plant-soluble carbohydrate reserves and senescence-key criteria for developing an effective grazing management system for ryegrass-based pastures: a review. *Australian Journal of Experimental Agriculture*, ***41*(2)**, 261-275.

Garcia SC, Fulkerson WJ, Brookes SU (2008) Dry matter production, nutritive value and efficiency of nutrient utilization of a complementary forage rotation compared to a grass pasture system. *Grass and Forage Science* **63**, 284-300.

Gawn TL, Harrington KC, Matthew C (2012)  Weed control in establishing mixed swards of clover, plantain and chicory.  *New Zealand Plant Protection* **65**, 59-63.

Ghanizadeh H, Harrington KC, James TK (2016) Genetic inheritance of restricted herbicide translocation in a glyphosate-resistant *Lolium perenne* population. *New Zealand Journal of Agricultural Research* **59**, 269-279.

Gibbs SJ, Saldais B (2014) Fodder beet in the New Zealand dairy industry. *Proceedings of the South Island dairy event, Invercargill, New Zealand* **4**, 1-8.

Gourley CJP, Dougherty W, Weaver DM, Aarons S, Awty IM, Gibson DM, Hannah MC, Smith AP, Peverill KI (2012) Farm-scale nitrogen, phosphorus, potassium and sulphur balances and use efficiencies on Australian dairy farms. *Animal Production Science* **52**, 929–944.

 Harmer M, Stewart AV, Woodfield DR (2016) Genetic gain in perennial ryegrass forage yield in Australia and New Zealand. *Journal of New Zealand Grassland* **78**:133-138

Harrington KC, Ghanizadeh H (2017) Herbicide application using wiper applicators – a review. *Crop Protection* **102,** 56-62.

 Harrington KC, Popay AI, Robertson AG, McPherson HG (1988)  Resistance of nodding thistle to MCPA in Hawkes Bay. *Proceedings New Zealand Weed and Pest Control Conference***41**,219-222.

Harrison, M. T., Christie, K. M., & Rawnsley, R. P. (2017). Assessing the reliability of dynamical and historical climate forecasts in simulating hindcast pasture growth rates. *Animal Production
Science*, ***57*(7)**, 1525-1535.

 Hayes RC, Li GD, Sandral GA, Swan TD, Price A, Hildebrand S, Goward L, Fuller C, Peoples MB (2017) Enhancing composition and persistence of mixed pasture swards in southern New South Wales through alternative spatial configurations and improved legume performance. *Crop and Pasture Science* **68**, 1112-1130.

Hedley C, Ekanayake J, Roudier, P (2012). Wireless soil moisture sensor networks for precision irrigation scheduling. In Workshop abstracts, advanced nutrient management: Gains from the past-goals for the future (p. 85).

Hedley CB, Roudier P, Ekanayake J (2013). Wireless soil sensing technologies supporting variable rate water management. In Invited presentation for the Precision Water Management Symposium, International Annual Meetings of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Hill BD (2014) Investigating the Dietary cation-anion difference (DCAD) of *Plantago lanceolata* and its potential as a pre calving forage for dairy cows. Honours thesis, University of Tasmania.

IARC (International Agency for Research on Cancer) (2015) Glyphosate. *Report Monograph* **112**, Leon, France, pp. 1-92. )

Jacobs JL, Hill J, Jenkin T (2009) Effect of different grazing strategies on dry matter yields and nutritive characteristics of whole crop cereals. *Animal Production Science* **49**, 608-618

Jones HG (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany* **55**, 2427-2436.

Keating BA, Carberry PS, Bindraban PS, Asseng S, Meinke H, Dixon J (2010) Eco-efficient agriculture: concepts, challenges, and opportunities. *Crop Science* **50**, 109-119.

Lee C, Henshal, JM, Wark TJ, Crossman CC, Reed MT, Brewer HG, O-Grady J, Fisher AD (2009) Associative learning by cattle to enable effective and ethical virtual fences. *Applied Animal Behaviour Science* **119**, 15-22.

Lee JM, Matthew C, Thom ER, Chapman DF (2012) Perennial ryegrass breeding in New Zealand: a dairy industry perspective. *Crop and Pasture Science* **63**, 107-127.

Lee JM, Hemmingson NR, Minnee EM, Clark CE (2015) Management strategies for chicory (*Cichorium intybus*) and plantain (*Plantago lanceolata*): impact on dry matter yield, nutritive characteristics and plant density. *Crop and Pasture Science* **66**, 168-183.

Lin Z, Cogan NOI, Pembleton LW, Spangenberg GC, Forster JW, Hayes BJ, Daetwyler HD (2016) Genetic Gain and Inbreeding from Genomic Selection in a Simulated Commercial Breeding Program for Perennial Ryegrass. *The Plant Genome* **9,** 1-12.

Lusk CS, Hurrell GA, Harrington KC, Bourdôt GW, Saville DJ (2015)  Resistance of *Ranunculus acris* to flumetsulam, thifensulfuron-methyl and MCPA in New Zealand dairy pastures.  *New Zealand Journal of Agricultural Research***58(3)**, 271-280.

 Macdonald KA, Glassey CB, Rawnsley RP (2010) The emergence, development and effectiveness of decision rules for pasture based dairy systems. In *Australasian Dairy Science Symposium: Meeting the Challenges for Pasture-Based Dairying,* pp. 199-209.

 Malcolm BJ, Cameron KC, Di HJ, Edwards GR, Moir JL (2014) The effect of four different pasture species compositions on nitrate leaching losses under high N loading. *Soil Use and Management* **30**, 58-68.

Marsh D. (2012) Water resource management in New Zealand: jobs or algal blooms? *Journal of Environmental Management* **109**, 33-42.

 Marquard E, Weigelt A, Temperton VM, Roscher C, Schumacher J, Buchmann N, Fischer M, Weisser WW, Schmid B (2009) Plant species richness and functional composition drive overyielding in a six‐year grassland experiment *Ecology* **90**, 3290-3302.

McCarthy AC, Hancock NH, Raine SR (2010). VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. *Computers and Electronics in Agriculture* **70**, 117-128.

McCarthy AC, Hancock NH, Raine SR (2014). Development and simulation of sensor-based irrigation control strategies for cotton using the VARIwise simulation framework. *Computers and Electronics in Agriculture* **101**, 148-162.

McCarthy S, Hirst C, Donaghy D, Gray D, Wood B (2014) Opportunities to improve grazing management. *Proceedings of the New Zealand Grassland Association* **76**, 75-80.

McDowell RW (2017). Does variable rate irrigation decrease nutrient leaching losses from grazed dairy farming? *Soil Use and Management* **33**, 530-537.

McLaren DK, Pembleton K (2015) Comparing within paddock yield variability of perennial ryegrass monocultures and perennial ryegrass, white clover and plantain mixtures using yield mapping. *17th Australian Society of Agronomy Conference,* Australian Society of Agronomy, Hobart, TAS, pp 1-4.

McDonagh J, O’Donovan M, McEvoy M, Gilliland TJ (2016) Genetic gain in perennial ryegrass (*Lolium perenne*) varieties 1973 to 2013. *Euphytica* **212**:187-199.

Min BR, Barry TN, Attwood GT, McNabb WC (2003) The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. *Animal Feed Science and Technology* **106(1-4)**, 3-19.

Mitchell KJ (1953) Influence of light and temperature on the growth of ryegrass (*Lolium spp*.) I. Pattern of vegetative development. *Physiologia plantarum* **6(1)**, 21-46.

Moot D (2014) A review of recent research and extension on dryland lucerne in New Zealand. *Proceedings of the New Zealand Society of Animal Production* **74**, 86-93.

Muir SK, Ward GN, Jacobs JL (2014) Milk production and composition of mid-lactation cows consuming perennial ryegrass- and chicory-based diets. *Journal of Dairy Science* **97**, 1005-1015.

Nie ZN, Miller S, Moore GA, Hackney BF, Boschma SP, Reed KFM, Mitchell M, Albertsen TO, Clark S, Craig AD, Kearney G, Li GD, Dear BS (2008) Field Evaluation of perennial grasses and herbs in southern Australia. 2. Persistence, root characteristics and summer activity. *Australian Journal of Experimental Agriculture* **48**, 424-435.

Nie Z, Norton MR (2009) Stress tolerance and persistence of perennial grasses: the role of the summer dormancy trait in temperate Australia. *Crop Science*, **49**, 2405-2411.

 Pembleton KG, Rawnsley RP (2012) Frost risk associated with growing maize for silage on Tasmanian dairy farms. *Proceedings of 16th Australian Agronomy Conference*, Australian Society of Agronomy, Armidale, NSW.

Pembleton K (2015) MMFF1 More Milk From Forages: Developing forage systems to meet the challenges for cool temperate pasture based dairy systems. Final Report to Dairy Australia. Tasmanian Institute of Agriculture, Burnie, Tasmania.

Pembleton K, Hill B, Rawnsley R (2015a) Response of the DCAD of plantain to potassium fertilisation. *Proceedings of* *17th Australian Society of Agronomy Conference,* Australian Society of Agronomy, Hobart, TAS, pp 1-4.

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

Pembleton KG, Hills JL, Freeman MJ, McLaren DK, French M, Rawnsley RP (2016) More milk from forage: milk production, blood metabolites, and forage intake of dairy cows grazing pasture mixtures and spatially adjacent monocultures. *Journal of Dairy Science* **99**, 3512-3528.

Pembleton KG, Rawnsley RP, Turner LR, Corkrey R, Donaghy DJ (2017) Quantifying the interactions between defoliation interval, defoliation intensity and nitrogen fertiliser application on the nutritive value of rainfed and irrigated perennial ryegrass. *Crop and Pasture Science*, **68(12)**, 1100-1111.

Pembleton LW, Shinozuka H, Wang J, Spangenberg GC, Forster JW, Cogan NOI (2015) Design of an F1 hybrid breeding strategy for ryegrasses based on selection of self-incompatibility locus-specific alleles. *Frontiers in Plant Science* **6,** 764-764.

Pembleton LW, Drayton MC, Bain M, Baillie RC, Inch C, Spangenberg GC, Wang J, Forster JW, Cogan NOI (2016) Targeted genotyping-by-sequencing permits cost-effective identification and discrimination of pasture grass species and cultivars. *Theoretical and Applied Genetics* **129**, 991-1005

 Pembleton LW, Inch C, Baillie RC, Drayton MC, Thakur P, Ogaji YO, Spangenberg GC, Forster JW, Daetwyler HD, Cogan NOI (2018) Exploitation of data from breeding programs supports rapid implementation of genomic selection for key agronomic traits in perennial ryegrass. *Theoretical and Applied Genetics,* 1-12.

Powles SB, Lorraine-Colwill DF, Dellow JJ, Preston C (1998)  Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Science* **57**, 604-607.

Rawnsley RP, Chapman DF, Jacobs JL, Garcia SC, Callow MN, Edwards GR, Pembleton KG (2013) Complementary Forages - integration at a whole farm level. *Animal Production Science* **53**, 976-987.

Rawnsley RP, Langworthy AD, Pembleton KG, Turner LR, Corkrey R, Donaghy D (2014) Quantifying the interactions between grazing interval, grazing intensity, and nitrogen on the yield and growth rate of dryland and irrigated perennial ryegrass. *Crop and Pasture Science* **65**, 735-746.

Roberts A, White M, Lawrence H, Manning M (2011) When more is more-a prècis! In 'Occasional Report No. 24.  Adding to the knowledge base for the nutrient manager'. (Eds LD Currie, CL Christensen), pp. 1-5.

Roche JR, Freeman M, Irvine L (2008). Determining the effect of a reduced dietary cation-anion difference (DCAD) on the incidence of milk fever in a milk fever prone dairy herd. *DairyTas*, 4-16.

Roche JR, Berry DP, Bryant A, Burke CR, Butler ST, Dillon PG, Donaghy DJ, Horan B, Macdonald KA, Macmillan KL (2017) A 100-year review: A century of change in temperate grazing dairy systems. *Journal of Dairy Science* **100**, 10189-10233.

Rugoho I, Lewis H, Islam M, McAllister A, Heemskerk G, Gourley A, Gourley C (2018). Quantifying dairy farm nutrient fluxes and balances for improved assessment of environmental performance. *Animal Production Science*, **58**, 1656-1666.

Schmittmann O, Lammers PS (2017) A true-color sensor and suitable evaluation algorithm for plant recognition. *Sensors* **17**, 1823.

 Smolka M, Puchberger-Enengl D*,* Bipoun M, Klasa A, Kiczkajlo M, Smiechowski W, Sowinski P, Krutzler C, Keplinger F, Vellekoop MJ (2017) A mobile lab-on-a-chip device for on-site soil nutrient analysis. *Precision Agriculture* **18(2)**, 152-168.

Stott KJ, Gourley CJP (2016) Intensification, nitrogen use and recovery in grazing-based dairy systems. *Agricultural Systems* **144**, 101-112.

Sun XZ, Pacheco D, Luo DW (2016) Forage Brassica: a feed to mitigate enteric methane emissions? *Animal Production Science* **56**, 451-456.

Tharmaraj J, Chapman DF, Hill J, Jacobs JL, Cullen BR (2014) Increasing home-grown forage consumption and profit in non-irrigated dairy systems. 2. Forage harvested. *Animal Production Science* **54**, 234-246.

Totty VK, Greenwood SL, Bryant RH, Edwards GR (2013) Nitrogen partitioning and milk production of dairy cows grazing simple and diverse pastures. *Journal of Dairy Science* **96**, 141-149.

Unkovich M (2012) Nitrogen fixation in Australian dairy systems; review and prospect. *Crop and Pasture Science* **63**, 787-804.

Verdon M, Rawnsley R, Raedts P, Freeman M (2018) The behaviour and productivity of mid-lactation dairy cows provided daily pasture allowance over 2 or 7 intensively grazed strips. *Animals* **8**, 115.

Von Bueren S, Burkart A, Hueni A, Rascher U, Tuohy M, Yule I (2014). Comparative validation of UAV based sensors for the use in vegetation monitoring. Biogeosciences. Discussions **11**, 3837-3864.

Wang J, Pembleton L, Cogan N, Forster J (2016) Evidence for Heterosis in Italian Ryegrass (Lolium multiflorum Lam.) Based on Inbreeding Depression in F2 Generation Offspring from Biparental Crosses. *Agronomy* **6**, 49-49.

Wheeler DM, Ledgard SF, De Klein CAM, Monaghan RM, Carey PL, McDowell RW, Johns KL, (2003) OVERSEER® nutrient budgets–moving towards on-farm resource accounting.  *Proceedings of the New Zealand Grassland Association* **65**, 191-194.

Wigley K, Owens J, Trethewey J A, Ekanayake D, Roten R, Werner A (2017) Optical sensors for variable rate nitrogen application in dairy pastures. Journal of New Zealand Grasslands **79**, 217-222.

Williams GM, Aardema M, Acquavella J, Berry C, Brusick D, Burns MM, de Camargo JLV, Garabrant D, Greim HA, Kier LD, Kirkland DJ, Marsh G, Solomon KR, Sorahan T, Roberts A, Weed DL (2016) A review of the carcinogenic potential of glyphosate by four independent expert panels and comparison to the IARC assessment. *Critical Reviews in Toxicology* **46(S1)**, 3-20.

**Conflicts of interest**

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**Figure 1.** Stylised response frontiers for production (a) and input loss (b: as a surrogate for environmental impact) of a baseline dairy system (solid line). Theoretical responses are shown for dairy systems that i) have successfully integrated a new cultivar/forage species (long dashed line), ii) successfully utilised a technology to make more efficient use of inputs (short dashed line), or iii) failed to defend against an external/internal negative degradation (solid grey line).

**Table 1.** A summary of the effects on the production and input loss frontiers, labour requirements, animal welfare and competition from non dairy alternatives of various aspects of forage management within pastoral dairy systems.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Future forage management | Effect on the production frontier | Effect on the input loss frontier | Effect on  labour requirements | Effect on animal welfare | Effect on competition from non-dairy alternatives |
| Grazing management |  |  |  |
| Forecasting and decision support for grazing managers | Improved frontier efficiency | Improved frontier efficiency | Increases the skill set of management | Minor | Minor |
| Complementary forages |  |  |
| Individual crops grown in rotation with pastures | Most likely a negative effect on the production  frontier | Potentially negative or positive | Requires specialist skills | Minor | Minor |
| Dedicated annual cropping | Lifts the production frontier | Negative | Requires specialist skills | Minor | Minor |
| Complementary perennial species | Lifts the production frontier | Positive | Requires specialist skills | Positive | Positive |
| Pasture mixtures |  |  |
| Increased pasture diversity | Lifts the production frontier | Positive | Minor | Positive | Positive |
| Fertiliser |  |  |
| Soil testing methods and scale | Improved frontier efficiency | Positive | Minor | Minor | Minor |
| Chemicals use and restriction |  |
| Chemical control of weeds  | Negative effect on the production frontier | Potentially negative  | Potentially increase the skill set of management | Minor | Minor |
| Irrigation |  |  |
| Precision and smart irrigation technology | Improved frontier efficiency | Positive | Reduces requirement for labour/skills | Minor | Minor |
| Species improvement |  |  |
| New approaches to pasture improvement | Lifts the production frontier | Positive | Minor | Minor | Minor |
| Development of the next generation endophytes | Defends against frontier degradation | Minor | Minor | Positive | Minor |