Simulating plant growth in diverse pastures with new forage models in APSIM

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Abstract

Livestock farming in New Zealand has traditionally relied on grazing ryegrass-white clover pastures. However, there is an increasing interest in using alternative forage species and on increasing the number of species in the sward. The major purpose is to increase or maintain production while improving resource utilisation, thus reducing the risk of nutrient losses. Diverse pastures tend to have more stable yields and produce more balanced feed, but also have growth patterns that are different from those of traditional swards, which can be challenging to manage. Therefore, there is a need to develop our understanding and tools to help farm managers to implement and manage such systems. Here, we introduce three newly developed forage growth models (Chicory, Plantain, and WhiteClover) that can be used within the APSIM (Agricultural Production Systems Simulator) modelling framework. We demonstrate their performance to simulate monocultures, and show a preliminary test for mixed sward simulations. The models were compared with an experimental dataset from the Waikato region, New Zealand, under different N fertiliser rates. Biomass accumulation and N response were reasonably well described under monoculture; variation in species composition over time was also in general agreement with the observed data. We discuss some challenges with simulating diverse pastures, and point out directions for further experimentation as well as model development, so that recommendations for farmers can be made with greater certainty.

Additional keywords: Forages, chicory, plantain, white clover, nitrogen fertiliser, systems modelling

Introduction

Livestock production systems in New Zealand are typically based on mixed pastures that are grazed by ruminants all year round. The traditional pasture is a binary mixture containing perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). The widespread adoption of this mixture reflects the synergy between the two species: they are easy to establish, have complementary growth patterns, can produce high quality feed, and tolerate a wide range of environments and grazing management (Kemp *et al*., 2000; Thorrold and Doyle, 2007; Vibart *et al*., 2016). Moreover, grazing management requirements of this combination are well understood by farmers. There are, however, several issues with this combination. For instance, the shallow rooting systems of these species leads to reduced yield when soil moisture is limiting; another problem is the low feed quality in spring because of reproductive growth of ryegrass. The generally high nitrogen (N) content of the herbage can also lead to the deposition of urine with high concentrations of N by grazing animals, which is the major source of N losses from grazed pastures (Di and Cameron, 2007; Eckard *et al*., 2007; Snow *et al*., 2017). The environmental impact of livestock production has become a concern in many regions, and farmers are under increasing pressure to reduce nutrient losses whilst maintaining profitability (Clark *et al*., 2007; Monaghan and de Klein, 2014).

The limitations of the traditional binary mixed pasture have led to increased interest in the use of alternative forage species, such as forbs, and on increasing the number of species in the sward. The importance of plant species diversity for enhancing ecosystem function has been debated by ecologists for some time (e.g. Tilman *et al*., 1996; Sanderson *et al*., 2005; Lemaire *et al*., 2011). Reported benefits include increased total biomass production, greater yield stability, improved soil quality and protection, improved water and nutrient use, and increased resistance to pests and weed invasion. Increasing species diversity is therefore an ecological approach to add desirable plant traits to a pasture. A number of studies have shown that herbage productivity of diverse pastures can match or exceed that of traditional pastures, especially when using forages that are active at low temperatures or have deep roots to access more soil water during summer (Sanderson *et al*., 2005; Nobilly *et al*., 2013; Vibart *et al*., 2016). Diverse pastures can also take up greater quantities of N from the soil compared with the traditional mix (Malcolm *et al*., 2014; Vibart *et al*., 2016). Both milk and meat production have been shown to be maintained or enhanced when animals graze multiple species swards (Tracy and Faulkner, 2006; Pembleton *et al*., 2015; Bryant *et al*., 2017). Introducing forbs to typical grass-clover pasture can also reduce the N load deposited via urine, either because of a more balanced feed quality or as a dilution effect (Woodward *et al*., 2012; Beukes *et al*., 2014; Bryant *et al*., 2017).

Several species are being considered for incorporation into diverse mixtures in temperate climates (Nobilly *et al*., 2013; Vibart *et al*., 2016; Bryant *et al*., 2017). These include legumes, such as red clover (*Trifolium pratense* L.) and lucerne (*Medicago sativa* L.), forbs, such as chicory (*Chicorium intybus* L.) and plantain (*Plantago lanceolata* L.), as well as a variety of grasses, such as tall fescue (*Festuca arundinacea* Sch.), prairie grass (*Bromus willdenowii* Kunth). Plant breeders have also been developing cultivars of perennial ryegrass and white clover with alternative traits, for example, deep root systems or high sugar content (Edwards *et al*., 2007; Crush *et al*., 2010; Snow *et al*., 2013). These plants offer a wide variety of traits that can improve a pasture, but they also have shortcomings, and their success in a mixed sward is determined by several environmental and management factors. Thus, to implement a diverse pasture successfully, it is important to identify which species to use for a given purpose (e.g. increase biomass production in summer, or reduce animal N excretion). Quantifying the performance of these alternative species when used in mixed swards and under different management is still an issue that needs further study (Sanderson *et al*., 2004; Nobilly *et al*., 2013; Pembleton *et al*., 2015). The addition of alternative species can also change the pasture's seasonal growth pattern. Some species grow more vigorously than the traditional ryegrass/white clover mixture in some periods, notably in spring/summer (Sanderson *et al*., 2005; Nobilly *et al*., 2013; Elgersma *et al*., 2014), and this may be challenging to manage within traditional farming systems. A diverse plant community will also shift in composition over time as a result of several factors, such as environmental conditions and preferential grazing. This means that feed availability as well as its quality are different from that of a traditional pasture, and these may change over time (Sanderson *et al*., 2005; Pirhofer-Walzl *et al*., 2011; Pembleton *et al*., 2015; Bryant *et al*., 2017).

Considerable research effort has, and still is, being put on trying to understand the changes in pasture production and quality caused by the introduction of alternative species, and the implications for farm management as well as economic and environmental outcomes. However, there are few recommendations on how to implement diverse pastures, which species to use, and how to manage them. Consequently, adoption of this practice by farmers has been limited. The lack of guidelines should not be surprising given the variety of potential species to use and the complexity of interactions among them, the environment, and management. Adoption of diverse pastures by farmers and the eventual fulfilment of their purpose (whether economic or environmental) depends on having clear demonstration of their impacts and guidelines on when and how to use mixed pastures. Given the complexity of such practice, there is a need to develop tools for helping farmers to implement and manage alternative mixed pastures. It is also crucial that the relevant impacts are recognised by regulators and accounted for in any compliance tool. For New Zealand, this means including the effect of alternative species and diverse pasture in tools such as the OVERSEER® Nutrient Budget (Wheeler *et al*., 2011; Monaghan and de Klein, 2014), which is used by both farmers and regional councils. Considering the limitation in scope and environmental conditions that can covered by experimentation, modelling must be an integral part of studying alternative and diverse pastures. Process-based, systems modelling can be used to complement and extrapolate findings from field research studies (e.g. Silvertown *et al*., 1992; Snow *et al*., 2013; Vogeler *et al*., 2017). Although such models may be too complex for use as decision support, they are very important for research, and they can also be used to derive simpler tools for farm managers and policy makers (Khaither and Erechtchoukova, 2007; Vogeler *et al*., 2011; Cichota *et al*., 2012).

The Forages for Reduced Nitrogen Leaching (FRNL) programme has fostered a series of studies on alternative forages and their management (among other issues), aiming to maintain production and reduce the environmental impact of grazing systems (e.g. Beukes *et al*., 2017; Carlton *et al*., 2017; Martin *et al*., 2017). Part of the work involves the development of animal and plant models that can be used to analyse the programme's experimental results. Since the modelling is process-based, these tools will also be able to explore future scenarios, helping to clarify the implications and devise guidelines for the use of alternative species and mixed pastures. In this work we introduce three of the forage models being developed in FRNL, and demonstrate their potential use and limitations, with special focus on simulating multiple-species pastures. We then discuss some of the challenges of developing and setting up simulations of farm systems which use diverse pastures.

Materials and Methods

Model description

All the development has been made using the agricultural production system simulator (APSIM) next generation (Holzworth *et al*., 2014, see also www.apsim.info). APSIM is a modular framework designed to simulate long-term dynamics in agricultural systems. It is a convenient platform for developing plant models, as it already contains models for soil water and N processes as well as the infrastructure for handling weather data and simulating management actions. In APSIM next generation, the Plant Modelling Framework (PMF) is the main structure for building plant models (Brown *et al*., 2014; Holzworth *et al*., 2018). PMF is also a modular tool, composed of sub-models describing the plant organs, phenology, plant structure, and the various processes defining the plant's physiological functions (e.g. photosynthesis, uptake). Interactions between plants and the environment are simulated using the MicroClimate and SoilArbitrator models. MicroClimate regulates above-ground competition, computing light interception and evapotranspiration, plus their partitioning among existing plants. Below-ground competition is mediated by the SoilArbitrator model, partitioning water and nutrient based on plants' root distribution and potential demands.

There are several crop models developed or under development based on APSIM-PMF. Here we introduce three of these models, the Chicory, Plantain, and WhiteClover models, and demonstrate their use in single- as well as multiple-species swards. For the mixed swards, AgPasture was used to simulate perennial ryegrass growth (Li *et al*., 2011; Vogeler and Cichota, 2016). The forage models were developed after a literature review of the botanical aspects of each species as well as agronomic trial datasets. As these models were developed using PMF, their general structure has similarities (more details about model structure in Brown *et al*., 2011; Brown *et al*., 2014; Khaembah *et al*., 2017), but each was parameterised separately using species-specific data and botanical information. General similarities include using the SimpleLeaf approach to describe the canopy (leaf organ and its processes, chiefly photosynthesis) and a simplified consideration of the reproductive parts (flowers and seeds). SimpleLeaf is a PMF sub-model that simplifies canopy structure; that is, it does not explicitly separate leaves by age or placement, but it includes variations in plant height (which are important for simulating competition for light). Photosynthesis is described using the radiation use efficiency (RUE) approach (Wang *et al*., 2002; Brown *et al*., 2014), with each species having its specific RUE value, light interception coefficient, and limiting functions due to environmental factors (CO_2, temperature, vapour pressure, as well as water and N availability). The reproductive parts, flowers and seeds, are simulated as a single organ, termed inflorescence. This reflects the complexity of the reproductive phase in these species and the lack of specific data for parameterisation. Plants of these species have flower buds and open flowers, as well as young and ripe seeds at the same time, which makes it very difficult to simulate each reproductive organ explicitly. Note also that plant models in APSIM describe an average population instead of a single plant, which results in even wider spread of reproductive development.

The three PMF model plants have significant differences regarding their types of organs. Chicory has stems that grow vigorously during the reproductive phase, reducing feed quality considerably, whereas plantain has only small stems, or flower stalks. White clover has prostrate stolons and only its petioles and flower peduncles, which rise in the canopy, are subject to defoliated. The biomass below ground for all species is described by two organs representing taproot and fine roots. For chicory the taproot is large and can penetrate deep in the soil profile, while it is much smaller in plantain. In white clover the taproot is generally ephemeral and thus represents a very small proportion of biomass in a sward population. The N-fixing nodules are simulated as plant organs in white clover. Fixation of atmospheric N is thus dependent on nodule biomass and is regulated by the plant, with N fixation proportional to N stress.

The basic development and tests for each model were done based on simulating monocultures. However, as part of APSIM-PMF the models can be used in simulations of multiple-species swards, with resource competition mediated by the MicroClimate and SoilArbitrator models. For the resource arbitration, these models exchange information with the various plants. Microclimate requires information about plant height, leaf area, and light extinction coefficient. Meanwhile, SoilArbitrator relies on an interactive exchange of demand-supply information between the soil and plants, with each plant determining potential uptake based on root distribution and the overall plant demand.

Experimental data

To demonstrate the performance of the forage models, we used a dataset from a field experiment conducted under the FRNL programme. The experiment was established at Scott Farm, near Hamilton, New Zealand, and ran from 2014 to 2016. The soil was a Horotiu Silt Loam (Typic Orthic Allophanic) and it was cultivated (Moulboard ploughed, power harrowed, and rolled) in spring prior to sowing (24 October 2014). The treatments comprised different forage species and six N fertiliser rates in a split-plot randomised factorial combination, with three replicates. The treatments relevant for this work were monocultures with forage chicory, plantain, and white clover, as well as a mixed pasture containing those species plus perennial ryegrass and lucerne. The nominal amounts of N fertiliser, applied as urea, were: 0, 50, 100, 200, 350, and 500 kg N/ha/yr, divided in 10 applications over the year. The actual fertiliser applications varied because they followed the defoliation schedule, the amount actually applied was about 80% of the nominal rates. The plots (3×2 m) were mowed regularly (about 4 cm height) following industry recommended practices (details in Martin *et al.*, 2017). On each harvest the biomass was removed from the field and weighted to determine herbage yield. The species composition of the mixed pasture was also determined in each of the harvests.

Results

The three forage models were able to simulate the biomass accumulation reasonably well for each of the species under monoculture (Figure 1). The R^2 values for the comparison using all data for each species varied between 0.84 and 0.93, but this measure was more variable for individual treatments (Table 1); the root mean square error (RMSE) ranged from 556 to 1930 kg DM/ha. Yield response to N fertiliser was greater for chicory and especially plantain, and greatest in the second growing season (Figure 1). White clover showed no significant effect of N fertiliser on herbage yield, which reflects its ability to fix N from the atmosphere. There was an effect of N rate in the mixed sward yields, but this was smaller than in the monocultures. This was a result of the much higher yields for low N fertiliser rates, which resulted from legumes making up a considerable proportion of the biomass in these treatments. The values for simulated mixed pasture are not shown, as it is not possible to compare observed and simulated swards fairly because the former included lucerne, for which there is no model currently available in APSIM next generation (it is under development). In general, yields were considerably lower for the mixed pasture simulations (values not shown) than the amounts harvested from the field experiment, and the differences were greater for the low-fertiliser treatments.

Table 1: Values for the coefficient of determination (R^2) and the root mean squared error (RMSE, kg/ha) between modelled and measured herbage yields for each species and fertiliser treatment (nominal N level, kgN/ha/yr).

Treatment	Chicory		Plantain		White Clover	
	R^2	RMSE	R^2	RMSE	R^2	RMSE
0N	0.585	1511	0.526	1886	0.933	980
50N	0.697	1486	0.697	1435	0.914	1283
100N	0.671	1678	0.867	963	0.889	1126
200N	0.916	1224	0.933	986	0.954	943
350N	0.934	1397	0.918	1409	0.962	556
500N	0.912	1929	0.874	1765	0.948	777

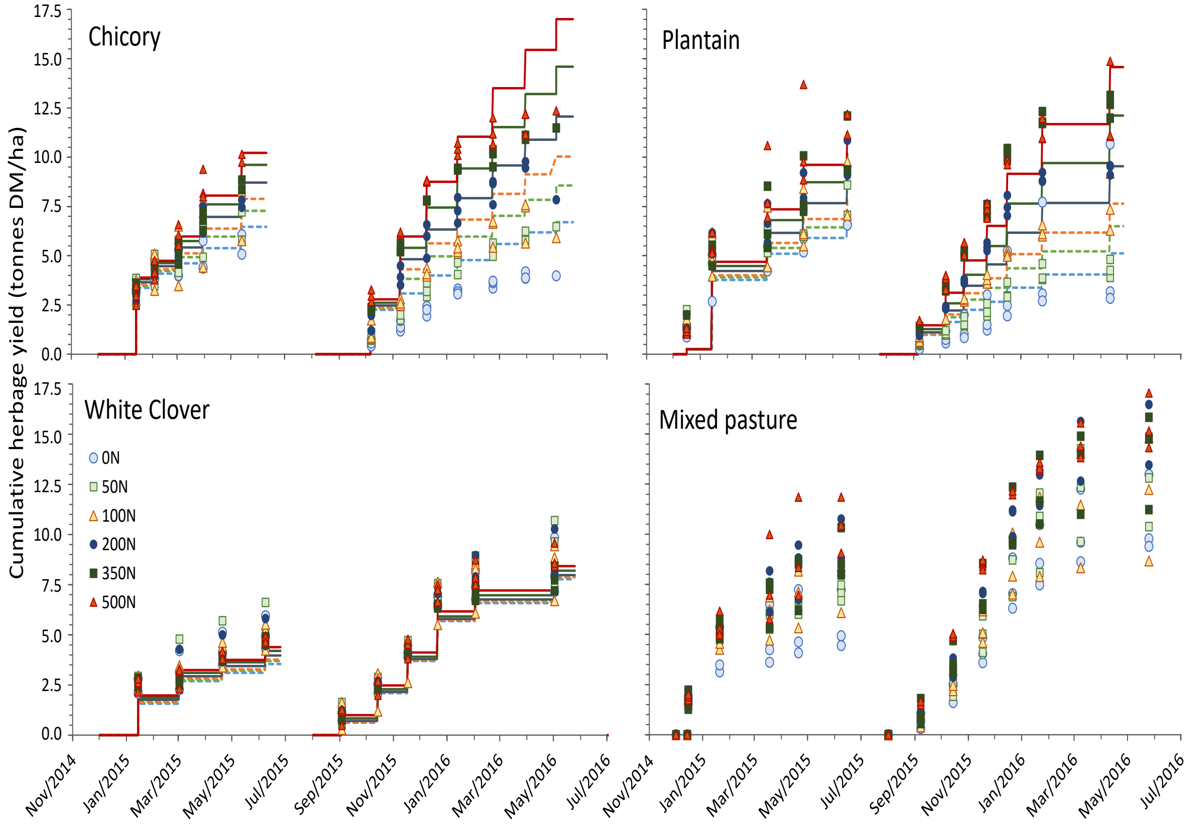

Figure 1: Measured (dots) and APSIM-simulated (lines) herbage yields for forage chicory, plantain and white clover grown under N fertiliser rates as monoculture and as mixed pasture; values are accumulated over each growing season. No simulated data are shown for mixed pasture, as a lucerne model is not yet available.

In general, chicory and plantain dominated the multi-species sward, but there were considerable differences between treatments regarding the proportion of the sward biomass for each species (Figure 2). At low N fertiliser rates, the fraction of legume increased over time, becoming dominant at the end of the experiment. There were less variations in sward composition as the amount of N fertiliser increased, with the simulation predicting the eventual elimination of perennial ryegrass and white clover from the mix. This was in agreement with the observed sward, which also had a small fraction of ryegrass and effectively no white clover. However, lucerne still made up a considerable proportion of biomass in all N rates (Figure 2).

Discussion and Conclusions

The increasing interest in the use of alternative pasture species and especially in increasing the diversity of pasture plant community of pasture means that research is needed to provide guidelines on how to implement and manage such systems. Given the high complexity of interactions among different species, the environment, and farm management, it is difficult to conceive that experimentation alone will provide enough information to devise recommendations tailored for various farming systems and for different eco-regions. The use of computer models alongside experimentation is key to filling this gap within a short-to-medium time frame. Process-based models, such as APSIM, are well suited for this task (Snow *et al*., 2013; Monaghan and de Klein, 2014; Beukes *et al*., 2017); such models provide a cost-effective way to explore diverse pastures under a variety of scenarios, including issues such as climate change adaptation. However, these models need to be well tested against a wide range of observed data so that we can have confidence in their predictions.

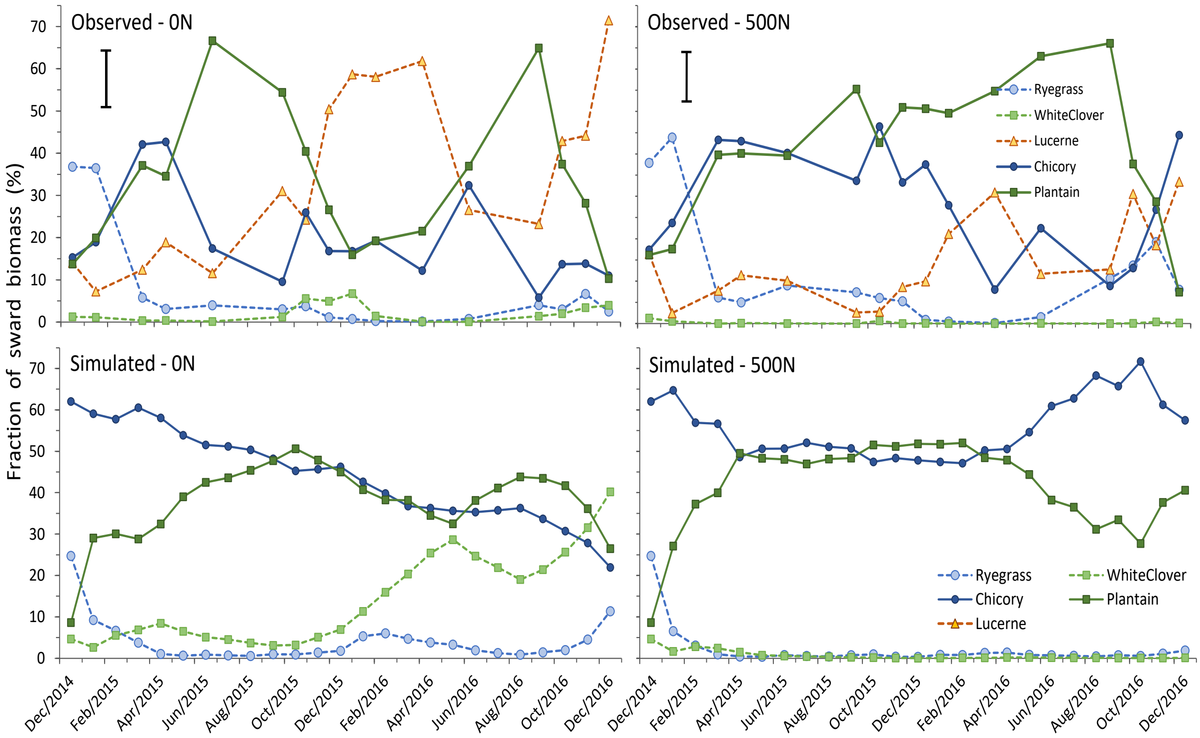

Figure 2: Observed (top) and APSIM-simulated (bottom) temporal variations of the fraction of sward biomass for forage chicory, plantain, white clover, ryegrass, and lucerne grown in a mixed pasture under no fertiliser or receiving 500 kg N/ha/yr. Vertical bars on top graphs represent the average standard deviation of observations. Note that the simulations did not include lucerne.

Three new forage models developed for the APSIM modelling framework have been introduced in this work, including their use for simulating multiple-species swards. The models performed reasonably well under monoculture; forage yield and their responses to N fertiliser generally compared well against the dataset from the Waikato region (Figure 1 and Table 1). Nevertheless, there were considerable deviations for chicory in the second growing season and, albeit small, the N response for clover was under-predicted, demonstrating that refinements are needed to improve the modelling framework. Although only one observed dataset was shown here, the models were developed based on an extensive literature review and tested against additional datasets; more information is available in the APSIM documentation (www.apsim.info). There is still a need for more datasets and tests, to increase confidence in the models as well as to further develop them, for instance to better reflect differences between cultivars.

The testing of the model under mixed pasture shown here is still in early stages but has shown promising results. Species composition did vary over time and the general trends predicted by the model agreed with the observed data (Figure 2). For low rates of N fertiliser, legume content increased significantly, whereas fast-growing broad-leaved species such as chicory and plantain dominated the swards under high N rates. Perennial ryegrass content was low in both observed and simulated swards, although there were some signs of increases by the end of the field experiment. The predominance of forbs and low ryegrass content may be considered counter-intuitive, as forb content tends to decrease sharply after the first year in grazed swards (e.g. Sanderson *et al*., 2005; Malcolm *et al*., 2014). This may reflect the fact that the experiment was managed as cut-and-carry, which cannot represent issues associated with grazing that tend to be more deleterious to forbs, such as preferential grazing or trampling. It was not sensible to compare the simulated mixed pasture directly with observed values, as APSIM does not yet have a lucerne model available and this species made up a considerable fraction of the sward biomass in all treatments. The fact that the simulated mixed pasture produced less biomass than the experimental sward requires further investigation; however, it is not totally surprising. White clover alone would not grow enough to represent the legume fraction present in the experimental sward, especially since lucerne has a much deeper root system and is thus more competitive during summer.

Advocacy for the use of diverse pastures has been presented in the scientific literature for some time (e.g. Tilman *et al*., 1996; Sanderson *et al*., 2005; Lemaire *et al*., 2011). These works include descriptions and rationale for some of the benefits, but data-based demonstrations are quite rare and/or localised. The complexity of mixed pasture, the importance of species composition, and the large effect of management means that there is still a need for further research on this practice. Systems modelling is a key approach to complement and enhance experimentation, but this needs to be an interactive process. Models need detailed experimental data to be developed and tested but can also supply information to guide experimentation (e.g. Snow *et al*., 2013; Vogeler *et al*., 2017). With robust models, predictions and extrapolations can then be meaningfully made. This work highlights a few of the challenges that require attention or caution when using data and models. For instance, datasets from only a few locations and of limited duration can restrict the range of management and especially environmental conditions against which the model can be tested. The experiment used here provided a wide range of N rates, but the effect of these were mostly noticeable in the second year. By the end of the experiment ryegrass content was starting to increase, so a third season's data would have provided useful information. In addition, the experiment did not explore the effects of irrigation or soil type; even considering all the experiments available to develop the plant models, the range of variations is quite limited. The cut-and-carry management of the experiment differs considerably in terms of selection pressure compared with grazing by animals. This is an important factor that still needs further studies in general, and model development in particular.

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