Inter-annual variability in pasture herbage accumulation in temperate dairy regions: causes, consequences, and management tools

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Abstract. Inter-annual variation in pasture herbage accumulation rate (HAR) is common in temperate dairy regions, posing challenges for farmers in the management of dairy cow feeding and of pasture state. This paper reviews the biophysical factors that cause inter-annual variation, considers some of its consequences for the efficient harvest of pasture, and discusses the basis for decision rules and support tools that are available to assist New Zealand and Australian farmers to help manage the consequences of an imbalance between feed supply and demand. These tools are well-grounded in scientific research and farmer experience, but are not widely used in the Australasian dairy industries. Some of the reasons for this are discussed. Inter-annual variability in HAR cannot be removed, even with inputs such as irrigation, but reliable forecasts of pasture HAR for a month or more could greatly improve the effectiveness of operational and tactical decision-making. Various approaches to pasture forecasting, based on pasture growth simulation models, are presented and discussed. Some of these appear to have reasonable predictive ability. However, considerably more development work is needed to: (1) prove their effectiveness; and (2) build the systems required to capture real-time, on farm data for critical systems variables such as pasture herbage mass and soil water content to combine with daily weather data. This technology presents an opportunity for farmers to gain greater control over variability in pasture-based dairy systems and improve the efficiency of resource use for profit and environmental outcomes.

Keywords: Climate variability, decision rules, forecasting.

Introduction

Numerous reports have documented the close, positive relationship between the amount of pasture consumed per hectare and the operating profit of dairy systems using grazing in temperate regions of the world (*e.g.* Savage and Lewis 2005; Chapman *et al*. 2008). The efficient, direct harvest of pasture by grazing cows contributes strongly to the cost-competitiveness of the New Zealand and Australian dairy industries. This is unlikely to change in the near future despite rising challenges that are being confronted by these industries, such as the need to reduce their environmental footprint (Clark *et al*. 2007) and to adapt to a changing and variable climate. Dairy industries in other temperate countries also have opportunities to exploit low-cost pastures for feeding to increase their dairy output and farm productivity.

Each country has its own specific farm management challenges related to, for example, soil types and climate, but the principles of efficient use of pasture are common to them all. The critical on-farm decisions associated with these principles have been documented (*e.g.* Macdonald *et al*. 2010). They have generally been developed around ‘averages’ or expectations of what will happen, for example average pasture growth rates for each month of the year, mean total pasture harvested per farm, or mean animal energy requirements. Increasingly, research is addressing the spatial and temporal variability inherent in grazed pasture systems, for example in understanding the variability in pasture growth among paddocks/fields within a farm (Clark *et al*. 2010) and reasons for this, quantifying the effect of temporal and spatial scaling errors on the prediction of pasture intake by simulation models (Parsons *et al*. 2011), or understanding the importance of the urine patch for nitrate leaching losses and how to mitigate these impacts (Di and Cameron 2002).

One of the major sources of inefficiency in temperate, pasture-based livestock production systems is year-to-year variability in pasture growth, driven by the strong climate variability which is characteristic of such regions (Gentilli 1971). Variability can be reduced, for example by irrigation to counter the effects of variable rainfall/evapotranspiration, but the inputs required are not always available, and the variability can never be completely removed (*e.g.* Fig. 1d). The management skill of the farmer largely determines how well the farm system is maintained with respect to key indicators of productivity, such as average herbage mass (HM) across the farm or animal body condition score, when there is year-to-year variability in feed supply. The aim of this paper is to

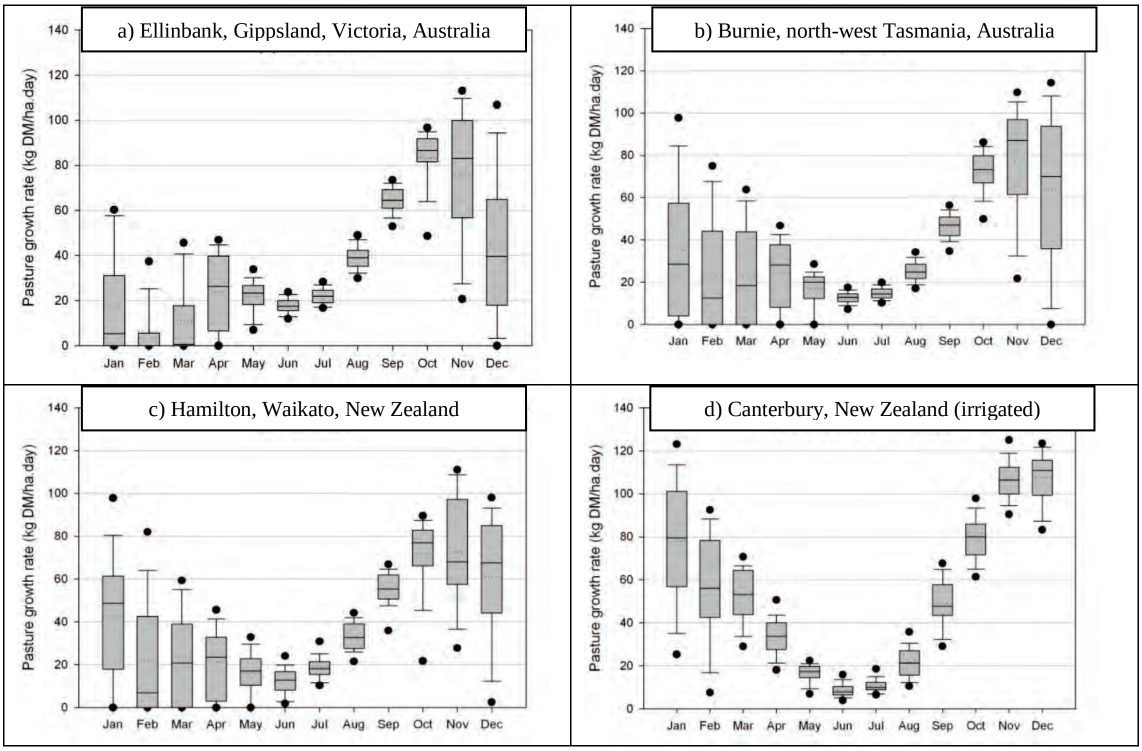

Figure 1. Modelled (using DairyMod) long-term monthly pasture growth rate distributions for dairy regions of: (a) Gippsland; (b) Tasmania, Australia (1907-2006); (c) Waikato; and (d) Canterbury (irrigated) New Zealand (1972-2006). Box plots show 10, 25, 50, 75, 90th percentiles. The dotted line is the mean and the dots are the 5 and 95th percentile values. From Chapman *et al*. (2009)

review the causes and consequences of seasonal and inter-annual variability in pasture growth, consider current management tools that are available to assist farmers to manage variability, and identify future research opportunities that might assist farmers to make better pasture and animal management decisions in the face of uncertainty.

Variability in pasture herbage accumulation: temporal scales

In temperate regions of the world, daily pasture herbage accumulation rate (HAR) is seldom constant, even over periods of 1-2 weeks. There are two main temporal scales of variation in HAR to consider in the design of efficient pasture-based livestock systems: 'seasonal', and 'inter-annual'. Seasonal variation refers to the month-by-month trend in HAR over a year which results from cyclic variation in the main environmental drivers of plant growth: soil water availability, temperature, and solar radiation. This is commonly presented using seasonal pasture growth curves that plot mean HAR by month of the year, using either empirical data (*e.g.* Radcliffe and Baars 1987) or the predictions of biophysical models (*e.g.* Chapman *et al*. 2009). Mean or median seasonal growth curves represent the *expected* growth pattern for a specific locality, and imply repeatable cycles of growth over time scales equating to months, or seasons (autumn, winter, spring, summer).

Inter-annual variation in HAR refers to the deviation from mean annual HAR that is observed when pasture growth outcomes are analysed for multiple years. Inter-annual variability in HAR results from climate variability which creates a unique, unfolding pattern of daily soil water availability, temperature and global radiation with direct consequences for plant physiology and growth. Depending on the management system in place, direct effects of climate variability on plant growth can compound to, for example, alter total HM / leaf area index (LAI), which in turn influences future HAR. Inter-annual variation in HAR is commonly quantified using simple ranges, or statistical measures such as percentiles, coefficients of variation, or standard deviations (Fig. 1).

Seasonal and inter-annual variation can be displayed on the same time scales, however the information they contain and implications for farm system management is quite different. The nature of these differences is developed in the following sections. The causes of seasonal and inter-annual variation are also different. In the former case, global radiation, temperature and soil water availability are all important and often changing simultaneously. For example, in temperate latitudes, irradiation and ambient temperature both decline through autumn until the winter solstice, after which irradiance (and day length) increases, and temperature also increases, though it usually lags the increase in irradiance.

The seasonal cycle of solar radiation intensity reaching the earth's surface, and ambient temperature, differs little year-by-year (*e.g.* average monthly CV of 8% for both factors for the period 1960 – 2012 at Elliott, northern Tasmania; R. Rawnsley, unpublished data) and this is a major driver of the seasonal pattern of pasture HAR. By contrast, mean monthly rainfall differs markedly between years (*e.g.* average monthly CV of 54% for the period 1960 – 2012 at Elliott, northern Tasmania; R. Rawnsley, unpublished data). Consequently, factors related to soil water usually explain the highest proportion of inter-annual variability in HAR: for example, 60% of variation in total annual HAR was attributed to differences in available soil water across Britain (Morrison *et al*. 1980), and 60% of the variation in total annual HAR of New Zealand pastures was explained by variation in spring-summer (September-February) rainfall totals (Radcliffe and Baars 1987).

Variability in pasture herbage accumulation: consequences for system performance

The consequences of variability in HAR for the productivity of pasture-based dairy systems generally emerge from the balance between feed supply and demand, where feed 'supply' refers to the total amount of nutrients/energy available from pasture, and feed 'demand' refers to the total amount of nutrients/energy required by grazing livestock for maintenance and production. The feed supply component is given by the mean monthly pasture HAR, against which feed demand can be plotted using the same units for each month. In Figure 2, the relationship is shown in terms of megajoules of metabolisable energy, since energy is the main factor limiting milk production and energy supply is not explained by HAR only: dry matter digestibility is also critical, and variable between months. Nonetheless, the relationship would be very similar if expressed in terms of kg DM/ha per day. Management policies such as stocking rate or calving date, which have a large bearing on total feed demand, are selected to align the feed supply and demand curves within the context of farm business goals. Other policies are then implemented to manage feed supply/demand imbalances depending on available resources (such as supplementary feed stocks and prices) and farmer attitudes to risk.

At this level of analysis, management decisions are being made on the basis of expected pasture supply. However, actual pasture supply will differ from year-to-year (Fig. 1, Fig. 2), and this cannot currently be predicted with any confidence (as discussed later). If actual HAR falls markedly short of expected HAR (*e.g.* Fig. 2C), then feed shortages will reduce animal intake and production, plus HM. Management responses are required to keep the system operating efficiently and sustainably. Excess (relative to requirements) HAR (*e.g.* Fig. 2A) will also have system consequences; for example through the build-up of HM leading to deterioration in sward structure and herbage nutritive value which can negatively impact subsequent dietary quality and intake. The various management 'levers' which can be used to control the consequences of inter-annual variability in HAR have been well documented by many authors (*e.g.* Sheath and Clark 1996). These include: increasing or decreasing inputs of nitrogen fertiliser, supplementary feed, or irrigation water, conserving excess feed as silage or hay, or altering the frequency and/or severity of grazing, all of which alter feed supply; or (in dairy systems) drying off cows, culling cows early, or moving to once-a-day milking, all of which alter feed demand. It is reasonable to propose that, in general, managers of highly profitable pasture-based farm businesses will execute this suite of management policies effectively to achieve best-possible pasture harvest efficiency and low average feed costs, whereas managers of less-profitable businesses are less proficient. However, it is difficult to find/collect sufficient unbiased data with which to test this proposition.

Decision-making: context and consequences

The foregoing discussion alludes to different levels of decision-making in pasture-based livestock production systems. Decision levels can be classified as strategic, tactical, and operational (Sheath and Clark 1996). Strategic decisions are re-visited infrequently (yearly, multi-year), and the changes made as a result of those decisions are difficult (and often costly) to implement. Examples in pasture-based dairy systems include stocking rate, cow breed, or calving date. Strategic decisions are supported by information on, for example, mean monthly HAR and a feed profile relating demand to supply over an average annual cycle to find the optimal (for the farm business goals) overall feed balance. At the other end of the scale, operational decisions are made daily or weekly. Where the focus is on maximising pasture harvest rates, these decisions can be supported by information on, for example, the pre- and post-grazing residual mass of pastures and/or a physiological stage of development *e.g.* leaf regrowth state (Fulkerson and Donaghy 2001). They are relatively simple and inexpensive to execute, but require monitoring

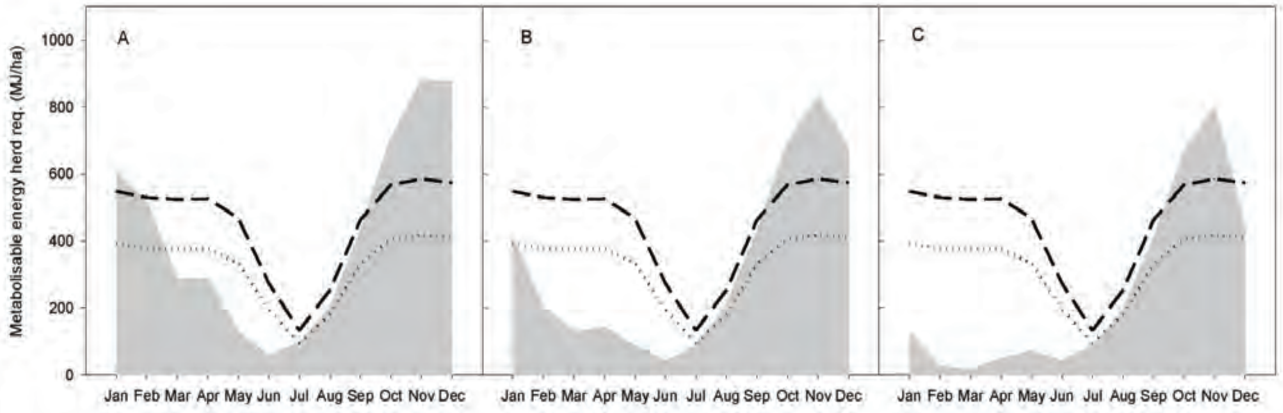

Figure 2. The daily metabolisable energy (megajoules (MJ) supply from pasture (shaded area) per hectare for the temperate region of north-west Tasmania, for a top 10% forage production year; (a) an average forage production year; (b) a bottom 10% forage production year; and (c) herd requirements stocked at 2.5 (dotted line) and 3.5 (dashed line) cows per ha, calving in early spring and producing 400 kg MS/cow.lactation. From Rawnsley *et al.* (2013)

information if they are to be executed well. Tactical decisions sit between these two levels, and are made over time scales of weeks or months. Examples of tactical decisions that influence pasture harvest rates include N fertiliser use, supplementary feeding, and the timing of removal of pasture area for silage conservation.

Breeding animals dominate the livestock inventory of dairy farms and, in New Zealand and Australian dairy systems, the stocking rate on any give farm is more-or-less fixed from year-to-year. Data on regional/national stocking rates per farm show only slow changes over time (*e.g.* DairyNZ 2012), reflecting good farmer understanding of the feed supply/demand balance and the consequences of under- or over-stocking. In an analysis which linked simulated pasture growth to actual dairy farm management information for several Australian and New Zealand dairy regions, Chapman *et al.* (2009) observed a close positive relationship between mean total annual pasture HAR and stocking rate at the regional level. The analysis also revealed a negative relationship between stocking rate and the magnitude of inter-annual variation on total HAR (as measured by CV%), leading to the conclusion that Australian and New Zealand dairy farmers are averse to risk when making strategic management decisions.

The next levels of decision-making, tactical and operational, are well-supported by decision rules that have emerged from 60 years of research and farmer experience (*e.g.* Macdonald *et al.* 2010). These rules are mostly based on animal and pasture targets, where the consequences of missing the target(s) have often been quantified. For example, Bryant (1990) concluded that NZ dairy farms operating at moderate stocking rates (2.8 – 3.3 cows/ha) require an average farm HM of 2400 kg DM/ha in mid September, and calculated that every 100 kg DM/ha HM less than target resulted in 3 kg milk solids per ha less production for the remainder of the lactation. This result emphasises the importance of using tools such as the Spring Rotation Planner (DairyNZ 2013a) to ensure that HM targets are met at critical times.

Two further notable examples of the importance of making timely, and accurate, tactical and operational decisions in response to inter-annual variation in pasture HAR can be drawn from Sheath and Clark (1996) and Fulkerson *et al.* (2005). Sheath and Clark (1996) investigated the impacts of adjusting the grazing rotation in response to a 50% reduction (compared with the long-term average) in pasture HAR in early spring (August-September) for a Waikato, New Zealand, dairy herd which starts calving on 20th July. They modelled two scenarios, using the dairy system model UDDER: maintaining the rotation length that would be applied in an average year through the period of growth restriction, or lengthening the rotation (offering less area per day) to maintain at least 1700 kg DM average HM over the farm. While the flexible grazing response resulted in a 33% reduction in pasture intake during August and September compared with the fixed rotation length, it allowed much higher HM to accumulate at the end of the period of growth restriction (2170 kg DM/ha versus 1220 kg DM/ha), resulting in 42% higher milk solids production per hectare for the whole lactation, and nearly double the operating profit per hectare for the season. Restrictions in early spring pasture HAR of the magnitude modelled by Sheath and Clark (1996) are rare (Fig. 1), but HAR may be 5-8 kg DM/ha per day lower than the median in August and September in 25% of years in the Waikato region (Fig. 1c). Decision support (DS) tools such as the Spring Rotation Planner have been developed for farmers in recognition of the importance of careful management of early spring HM on dairy farms in New Zealand.

Fulkerson *et al.* (2005) compared pasture harvest and milk production of groups of cows fed either a fixed daily amount of supplement (‘control’) or a variable amount of supplement (‘adjusted’) in the presence of between-paddock variation in pasture availability. In the adjusted group, total cow intake was similar each day (although the proportion of supplement and pasture varied according to pasture availability), whereas in the control group intake varied and pasture could be either under- or over-grazed depending on pasture availability. Fulkerson *et al.* (2005) concluded that the flexible management applied to the adjusted group resulted in sufficient spared pasture to produce 8.9 – 12.3% more milk solids per hectare compared with the control group. Inter-annual variability in HAR will inevitably lead to different pasture availability among paddocks from one year to the next. Again, DS tools have been developed to assist farmers to calculate pasture available per paddock, adjust areas allocated and/or supplements offered to meet intake requirements, and (where possible) conserve pasture surpluses (*e.g.* as silage) to fill feed gaps at other times of the year (Dobos and Fulkerson 2004, DairyNZ 2013b).

Decision support tools for coping with inter-annual variability in HAR

Decision support tools drive efficiency in pasture-based dairy systems through key biophysical indicators such as cow condition at calving, average HM across the farm at the start of calving, residual HM after grazing, and the management of spring pasture surpluses (Macdonald *et al.* 2010). They can therefore assist farmers to manage inter-annual variation in pasture HAR. Successful implementation of these DS tools requires: (1) quantitative animal and pasture targets that are closely related to productivity; (2) information on HM for all paddocks in the grazing rotation, collected frequently (*e.g.* weekly), which can be used to calculate, for example, a feed wedge and to estimate pasture HAR and intake (DairyNZ 2013b); (3) knowledge of likely rates of response to inputs, such as nitrogen fertilizer; (4) information on current animal production, condition score, and feed requirements; and (5) knowledge of the relative cost of different inputs that can be used to adjust for variable pasture supply, such as different types of supplementary feeds

This long list of requirements perhaps explains why the frequency of uptake of pasture and grazing DS tools on New Zealand and Australian dairy farms is quite low (approximately 15%, Mata *et al.* 2007), despite their relevance to farm profit. Rawnsley *et al.* (2010) conservatively estimated that farm walks to determine HM occur regularly on only 10% of Tasmanian dairy farms. One factor that may contribute to low rates of adoption of DS tools is the time required to collect data on HM from all paddocks on a regular basis using, for example, the rising plate pasture meter (Lile *et al*. 2001). Technologies which address this time constraint include those that can be towed behind, or attached to, all-terrain vehicles such as the C-DAX Rapid Pasture Meter (King *et al*. 2010). Alternative approaches to fully eliminate the need for an operator have been proposed, such as the use of satellite remote sensing (Mata *et al*. 2007) and the use of commercial digital video camera imagery acquired by an unmanned aerial vehicle (Kawamura *et al*. 2011).

Importantly, all of the monitoring information discussed above is retrospective, and its application is predicated on expectations of future HAR. For very short-term, operational decisions, this is adequate; but for tactical decisions with longer time horizons, uncertainty around future outcomes increases the risk of a poor decision being made. Currently, the only tool available in the domain of prediction is long-range weather forecasting, such as the seasonal rainfall outlooks published by the Australian Bureau of Meteorology (BoM) each month, for the next three months. Vizard *et al*. (2005) analysed BoM seasonal forecasts and actual rainfall for 262 townships across Australia from June 1997 to May 2005. They observed that the forecast variances were relatively small, that the forecasting system had low skill, and that substantial value to users would require new lead indicators with markedly better predictive characteristics than is currently the case. Improvements in seasonal forecast skill are likely to come from development of coupled ocean-atmosphere models, rather than relying on statistical approaches such as the Southern Oscillation Index, but progress is expected to be incremental with limited prospects for improvement over the next decade or more (Ash *et al*. 2007). This begs the question: are there other approaches or tools that could be developed for forecasting, and improving farmers' ability to match inputs and management responses to variability in pasture supply?

Tools for forecasting

Computer simulation models of pasture growth provide one source of possible pasture forecasting tools. Generally, biophysical simulation models contain too much complexity for application at farm level, and must be re-formulated to strike a balance between ease of use and the burden of parameterisation versus acceptable predictive accuracy. One example is PGSUS (Pasture Growth Simulator Using Smalltalk, Romera *et al*. 2010), which uses a modified version of a relatively simple climate-driven pasture model to predict the pasture growth trajectory between two points of HM measurement. Romera *et al*. (2010) reported that PGSUS estimated HM at intervals up to 28 days from the last observed data with a correlation co-efficient of approximately 0.9, and small bias. The model requires data for daily mean, maximum and minimum temperature, solar radiation, rainfall, and potential evapotranspiration. Such data are available electronically; in New Zealand through the Virtual Climate Station Network from the National Institute of Water and Atmospheric Research, and in Australia, the SILO database of the Bureau of Meteorology (Jeffrey *et al*. 2001). PGSUS includes empirical parameters which are adjusted to 'train' the model to match observed data at the individual paddock level, using all available measured data as it accumulates. When used to fill gaps in HM information, the tool is still 'hind-casting' but the training capacity of the model combined with development of forecast daily weather data could enable forward projections for up to 4 weeks, a useful window of time in relation to some operational and tactical decisions such as N fertiliser application.

The development of 'forecasting' tools for managing climate risk in the grazing industries has been slow relative to cropping systems. In dryland cropping systems, simulation tools such as 'Yield Prophet' are used to make decisions about nitrogen fertiliser inputs based on current soil water content and nitrogen availability in the soil, together with climate information drawn from the historical record to represent the range of possibilities for the season ahead (Hochman *et al*. 2009). Given the importance of soil moisture in pasture growth rate variation (Fig. 1), similar approaches have potential application to forecast pasture growth rates across dairy regions.

An example of the influence of soil water content at the beginning of September, October and November on future growth rates for Ellinbank in Gippsland, Victoria is shown in Figure 3. This indicates that soil water content in

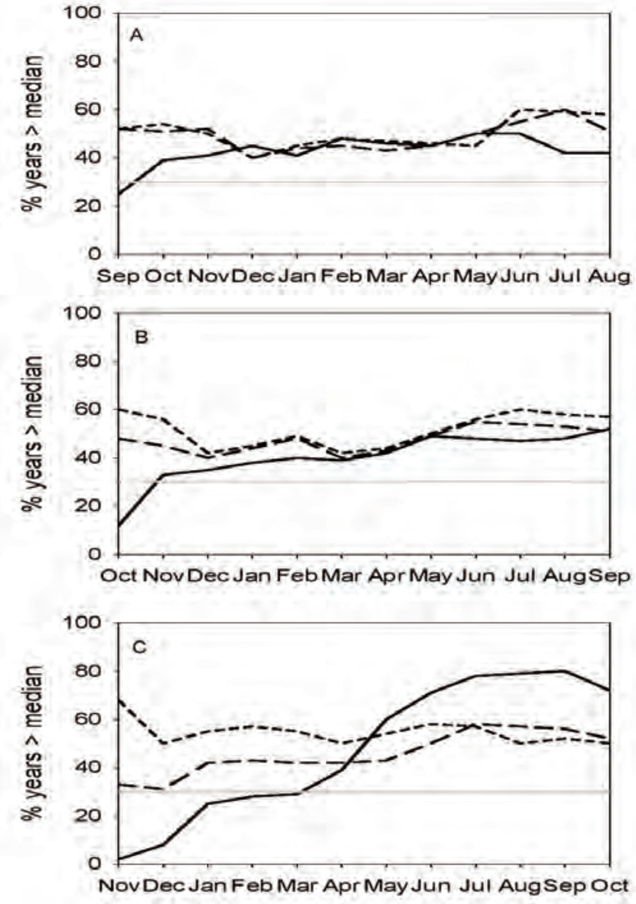

Figure 3. Effect of high (short dash), mid (long dash) and low (solid line) soil water content at the beginning of; (a) September; (b) October; and (c) November on the percentage of years in each soil water content category predicted above the long-term median for a perennial ryegrass-based pasture at Ellinbank, Victoria. The grey lines are 70% and 30% years above median. Approach adapted from Cullen and Johnson (2012).

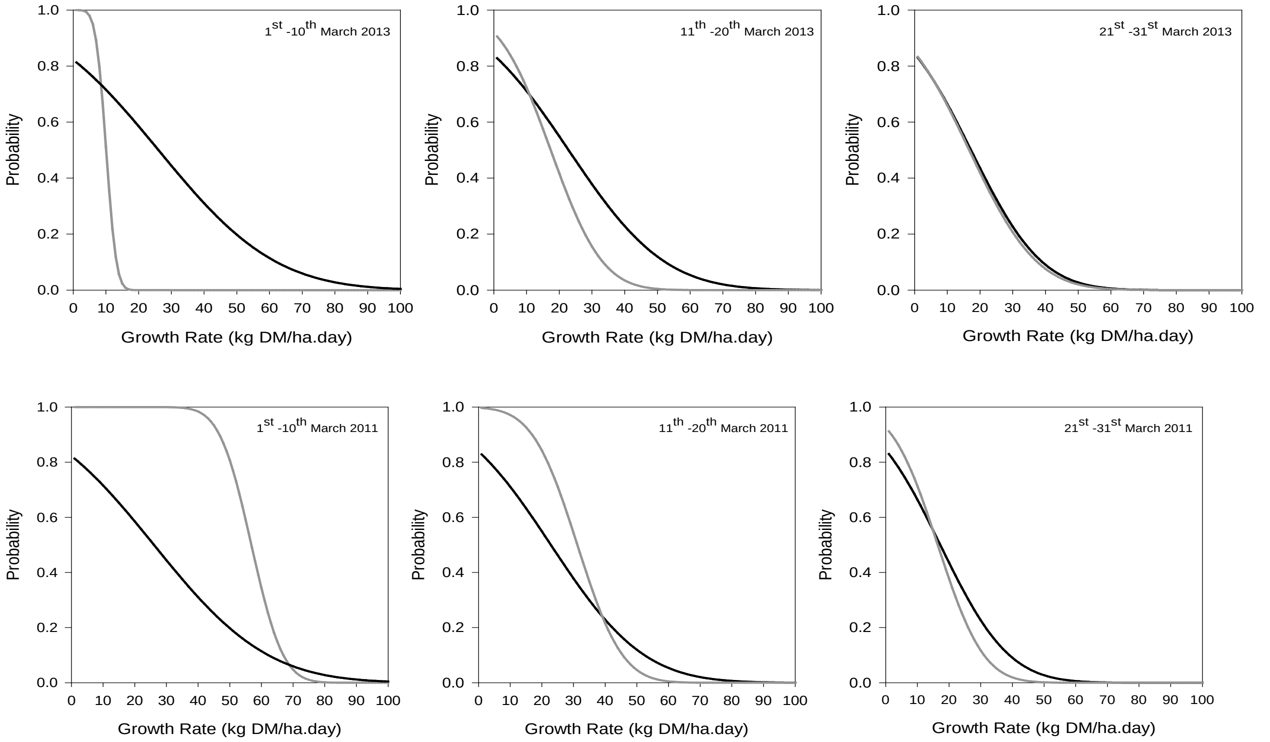

Figure 4. Cumulative distribution functions comparing the forecast pasture herbage accumulation rates (kg DM/ha.day) against the probability of exceedance for 1st -10th, 11th-20th and 21st to 31st March 2013 (top panel) and 2011 (bottom panel) using an historical (black line) and tactical (grey line) analysis for the region of Elliott, northern Tasmania. R. Rawnsley, unpublished data

September has little impact on future spring pasture growth rate, when rainfall is high and transpiration rates are increasing. However, in October and November when soil moisture is usually declining (and pasture growth variability is increasing, Fig. 1a), low soil water content is related to lower than long term average growth rates over the following 1-4 months. This information is necessarily probabilistic: using a threshold of 70% probability of being different from the median as an indication of when the forecast has sufficient skill for a producer to make a decision (Ash *et al.* 2007), the low soil water content has forecast skill in October for 1 month into the future and in November for 4 months.

Application of these principles to tactical and operational decision making on dairy farms would involve simulation of the farm system using measured climate data up to current day, then forecasting forward using historical climate data as an indication of what climatic conditions may occur over the next few weeks or months. An example of this approach is illustrated in Figure 4 where measured climate data is used up until 28th February to determine the current condition of the system. HAR is then simulated for the month of March, amending March climate data for the preceding 20 years. In comparison the historical analysis uses consecutive sequences of historical weather data to generate the variability in HAR for a given period, in this example for March. The important distinction between the two approaches is that the tactical analysis starts each simulation run at the same initial values and as such the tactical approach provides a much stronger indication of expected HAR over the short-term (Fig. 4). This is visible by comparing the projected growth for March 2013, following a dry summer (top panel Fig. 4), where the probability of achieving a HAR exceeding 15 kg DM/ha.day in the first 10 days of March is less than 3%. In comparison, the historical analysis indicates that for any given year the probability of HAR for this same period being greater than 15 kg DM/ha.day is 65%. A tactical analysis following a wet summer (see bottom panel of Fig. 4) indicates that there is 100% probability of HAR exceeding 30 kg DM/ha for the first ten days in March.

This information has clear implications for rotation planning and feed budgeting, but could also be adapted to assess the likelihood of efficient response to fertiliser application being obtained. In all these analyses, predictive skill comes from accurately defining the condition of the system on the first day of the simulation, with the variation in simulated outcomes increasing as the prediction moves further into the future (*e.g.* Cullen *et al.* 2008). In the examples provided here the emphasis is on soil moisture but important initial conditions may also include soil N availability, pasture mass and species composition. Regular measurement of parameters such as soil moisture and N are not practical across the range of paddocks with different soil types and variations in management on a dairy farm, so sound biophysical models are an essential pre-requisite for this type of analysis. In the example in Figure 4, the strength of the forecast signal for this environment and time period is quite transient lasting approximately 20 days. This highlights the need to establish automated processes for capturing and / or simulating initial conditions and updating the forecast.

Conclusions

Managing short-term variability in plant growth presents a greater challenge in grazing systems than in cropping systems. In grazing systems, the continual interaction between stock and pasture, and the requirement to feed the stock on a daily basis, adds further complexity, especially when pasture HAR is fluctuating week-by-week. There is a clear opportunity to further explore the potential for forecasting pasture growth to reduce some of the uncertainty that limits the effectiveness of tactical/operational decision-making in dairy systems. The development of such tools is more advanced in the cropping industry. Forecasting decision support tools for the management of inter-annual variability in pasture HAR in the dairy industry must meet the criteria for DS success proposed by Ash *et al.* (2007), *viz* that they should be: (1) reasonably accurate; (2) provide sufficient lead time for a decision to made; (3) have an economic and/or sustainability benefit for the whole system; and (4) be clearly communicated to the target audience.

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