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Pasture herbage mass, quality and growth in response to three whole-farmlet management systems

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Abstract. The effects of different whole-farm management systems were explored in a farmlet trial on the Northern Tablelands of New South Wales, Australia, between July 2000 and December 2006. The three systems examined were first, a moderate input farmlet with flexible grazing on eight paddocks considered ‘typical’ of the region (farmlet B), a second, also with flexible grazing on eight paddocks but with a high level of pasture renovation and increased soil fertility (farmlet A) and a third with the same moderate level of inputs as farmlet B but which practised intensive rotational grazing on 37 paddocks (farmlet C).

The changes in herbage mass, herbage quality and pasture growth followed a seasonal pattern typical of the Northern Tablelands with generally higher levels recorded over spring–summer and lower levels in autumn–winter but with substantial differences between years due to the variable climate experienced. Over the first 18 months of the trial there were no significant differences between farmlets in total herbage mass. Although the climate was generally drier than average, the differences between farmlets in pasture herbage mass and quality became more evident over the duration of the experiment. After the farmlet treatments started to take effect, the levels of total and dead herbage mass became significantly lower on farmlet A compared with farmlets B and C. In contrast, the levels of green herbage were similar for all farmlets.

Throughout most of the study period, pastures on farmlet A with its higher levels of pasture renovation and soil fertility, had significantly higher DM digestibility for both green and dead herbage components compared with pastures on either of the moderate input systems (B and C). Thus, when green herbage mass and quality were combined, farmlet A tended to have higher levels of green digestible herbage than either of the other farmlets, which had similar levels, suggesting that pasture renovation and soil fertility had more effect on the supply of quality pasture than did grazing management. This difference was observed in spite of the higher stocking rate supported by farmlet A after treatments took effect.

Levels of legume herbage mass, while generally low due to the dry conditions, were significantly higher on farmlet A compared with the other two farmlets. While ground cover on farmlet A was found to be less than the other farmlets, this was largely associated with the higher level of pasture renovation. Generally, all three farmlets had ground cover levels well above 70% for the duration of the experiment, thus being above levels considered critical for prevention of erosion.

A multivariate analysis showed that the main explanatory factors significantly linked ($P < 0.01$) with the supply of high quality herbage were, in decreasing order of importance, those related to season and weather, pasture renovation, grazing management and soil fertility. Measurements of net pasture growth conducted using a limited number of grazing exclosure cages on three paddocks per farmlet revealed clear seasonal trends but no significant ($P > 0.05$) differences between farmlets. However, *post hoc* estimates of potential pasture growth rate using remotely sensed MODIS satellite images of normalised difference vegetation index captured weekly from each farmlet revealed a significant ($P < 0.001$) relationship with the seasonal pattern observed in the measurements of pasture growth rate.

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Introduction

Managing pasture-based livestock enterprises on the Northern Tablelands of New South Wales (NSW), Australia, with its summer-dominant rainfall pattern, is known to be challenging due to common dry periods and frequent low winter temperatures and frosts in winter. While categorised within Australia’s ‘high-rainfall zone’, the region, which receives an average annual rainfall of ~780 mm, suffers from high-rainfall variability. When combined with high evaporation rates over summer and cold temperatures in winter, the result is a high level of variability in seasonal and annual pasture production. Maximum pasture growth normally occurs in spring and summer while the minimum typically occurs in winter. In addition to the effects of soil moisture and temperature, growth of pasture is governed by other factors including pasture botanical composition and soil fertility. For example, Cook *et al*. (1978*b*) found that phosphate-deficient soils in this region can lead to degraded pastures with few winter growing species, which can become dominated by summer-growing C_4 species such as red grass (*Bothriochloa macra*), which contribute little to the winter feed supply.

One of the key factors contributing to greater pasture production in the higher rainfall areas of temperate Australia has been the establishment and maintenance of perennial grasses as well as vigorous legumes (Archer *et al*. 1993; Scott *et al*. 2000). However, it has been widely recognised that retaining valuable perennial pastures in the high-rainfall temperate zone of Australia is difficult and requires careful management (Kemp and Dowling 2000).

If such perennial pastures become degraded, the direct costs of renovation and the indirect costs of loss of production during the re-establishment phase are considerable. Thus, it is important that desirable perennial pastures persist, even under high grazing pressure. Cullen *et al*. (2005) have suggested that to be economically and environmentally beneficial, sown pastures need to persist for at least 10 years. However, it appears that this goal is rarely achieved by most livestock producers in the high-rainfall zone (Reeve *et al*. 2000). At the start of the Cicerone Project (Sutherland *et al*. 2013), a survey of Northern Tablelands producers confirmed that the maintenance of the pasture feed supply and its quality, especially in dry years was one of the most important problems for graziers in this region (Kaine *et al*. 2013).

It is widely recognised that sowing perennial grasses, legumes and herbs (e.g. chicory) can increase animal productivity such as lamb growth rates and stocking rates (Holst *et al*. 2006). While it is recognised that sown pastures can lift animal production over the short term, livestock producers have expressed concern that, over time, such pastures can show poor persistence (Reeve *et al*. 2000), especially under drought conditions, leading to replacement by less desirable annual species and weeds (Jones 1996). According to Jones (1996), new approaches to grazing management are needed, in conjunction with greater nurturing of soils and vegetation, including native species, which have been disadvantaged in some past experiments where fertiliser was applied to the sown species and not to the native species (Jones 1996).

Maxwell (1990) has pointed out the challenges of understanding the effects of pastures on animals and *vice versa* due to the complexity of the 'ecology of the plant-animal interface', which determines both dietary intake and animal growth. For example, grazing management can be used to manipulate the quantity and quality of forage on offer (Harris 1978; Morley 1981; Hodgson 1990) as the intensity and frequency of defoliation by grazing animals, as well as their ability to selectively graze, all influence herbage mass, the proportion of green, the pasture species composition and also pasture quality.

Stocking rate is fundamentally linked to the pasture supply and, in particular, pasture growth rate. Although claims have been made that intensive rotational grazing can substantially increase stocking rates compared with continuous grazing (McCosker 2000), the evidence for this is scant and such systems remain highly controversial (Waugh 1997; Norton 1998; Saul and Chapman 2002). Using hypothetical calculations, Norton (1998) postulated that intensive rotational grazing may increase pasture production but to date little evidence has been provided to support these predictions.

Early studies of continuous vs. rotational grazing systems on both sown and native pastures have reported equivocal results in relation to animal production. In the case of sown pastures of phalaris, subterranean clover and lucerne, rotational grazing at 4- and 8-week intervals was found to be an unreliable method of increasing animal production above that achieved with continuous grazing (Moore *et al*. 1946).

With native pastures on the Northern Tablelands of NSW, Roe *et al*. (1959) showed little effect of rotational grazing v. continuous grazing on animal production whereas increasing stocking rate had a large effect on production. In addition, they showed that the availability of high quality green forage was the key pasture factor linked to animal productivity. Again, on the Northern Tablelands of NSW, Hamilton *et al*. (1973) showed that there was a critical limit of 550 kg (DM) of green herbage above which sheep were able to select a diet of higher quality than the quality of the feed on offer.

Summarising the pasture theme from the Sustainable Grazing Systems key program, Sanford *et al*. (2003) reported that the persistence of desirable perennial grasses in the high-rainfall zone of southern Australia depended on grazing rest, length of growing season, the proportion of native species, soil fertility and the presence of legumes. Legumes were favoured more by continuous than rotational grazing and by a higher stocking rate. However, there have been few studies which have attempted to study pasture and animal production at the level of complexity of a whole farm or farmlet. One such study, by Lambert *et al*. (1983) in hill country in New Zealand, assessed herbage accumulation on 10 farmlets on a total area of 99 ha, and found little difference between continuous and rotationally grazed pastures for sheep.

As recognised by Kemp *et al*. (2000), there is a need for different pasture management strategies to be tested 'at a commercial scale' in Australia. Thus, the Cicerone Project embarked on a study at a whole-farmlet scale, which examined, among other things, the influence of management on the growth, quality and persistence of pastures under dryland field conditions. Pasture responses to different levels of inputs (pasture renovation and soil fertility) and different grazing management strategies were recorded over 6.5 years in a whole-farmlet study on a total area of 159 ha. The key hypotheses examined were that either or both of the strategies of higher-input (farmlet A) or intensive rotational grazing (farmlet C) would result in enhanced herbage mass and/or pasture quality and/or pasture growth rates compared with the typical management system (farmlet B).

Materials and methods

The study site (lat.: 30°37′S; long.: 151°33′E), design and treatments adopted in the farmlet trial have been described in detail by Scott *et al*. (2013). The methods specific to this paper are described below.

Herbage mass

From March 2000 to February 2003, calibrated visual estimates of total herbage mass were taken together with each annual assessment of botanical composition. Thereafter, regular monthly calibrated visual assessments of total and dead herbage mass, percent green, digestibility of dead and green, legume mass and ground cover were carried out from April 2003 to December 2006.

The methods used for herbage mass assessments were based on the Botanal procedure (Tothill *et al*. 1978) complemented by the falling plate technique (Cayley and Bird 1991) and the experimental protocols developed for the Temperate Pasture Sustainability Key Program (Lodge 1996). Botanal (or the dry weight rank method) has been reported to be well suited to the collection of rapid and non-destructive estimates of herbage mass (Waite 1994). Similar methods, using visual, calibrated assessments of pasture mass have been used on each paddock of dairy farmlet trials in New Zealand for decades (Clark 2010).

At each of the earlier annual measurement dates, assessments were carried out along the same transect of each paddock of each farmlet. After observing pasture height and pasture density along the transect, a visual estimate of total herbage mass was recorded at ~20 points per transect and later calibrated with a series of five quadrats (300 by 500 mm) or, later, calibration rings, which were cut, dried and weighed at each sampling to represent the full range of herbage mass observed. For the later measurements taken at monthly intervals, visual assessments of herbage mass were calibrated using a Median Quadrat pasture frame (300 by 500 mm) (Bell 2007) at each site, then cut to ground level, dried for 48 h at 80°C and weighed. These herbage mass estimates and harvested calibration weights were entered into a spreadsheet template with separate data entry fields and calculated fields based on the calibration equations from estimates of herbage mass and digestibility (green and dead). This procedure of using a standard template ensured that the same data manipulations were always carried out.

Pasture quality

Concurrently with the monthly herbage mass estimates, an estimate of the digestibility of the herbage present was recorded as a score between 1 and 5. This score was based on the relative proportions of the feed on offer comprised of herbage ranging from low digestibility, mature, tussocky native grasses to green leafy plants of higher digestibility. The age and maturity of any green regrowth was also taken into account. Thus, a pasture assigned a score of 1 was judged to have the highest proportion of low digestibility herbage with the oldest regrowth, while a score of 5 represented the pasture judged to have the highest proportion of green digestible leaf and the youngest regrowth at that particular sampling.

Five harvested calibration samples (cut with clippers to represent that portion of the plants able to be grazed) were subsequently sorted into green and dead portions, dried for 48 h at 80°C, the fractions weighed and then ground through a 1-mm sieve for scanning with near-infrared spectroscopy (Smith and Flinn 1991; Adesogan *et al*. 2000). Four grams of duplicate samples were packed into sample cups and scanned using a 6500 monochromator (NIRSystems, Silver Spring, MD, USA) reflectance detector near-infrared spectrophotometer that scanned from 400 to 2500 nm. A reflectance spectrum was obtained from two duplicate scans per sample. An average spectrum was computed from the data and the spectrophotometer software (NSAS version 3.20) was used to calculate percent digestibility, for both green and dead herbage material based on previous calibration curves developed using laboratory analyses of pasture plant digestibility and crude protein (L. Lisle, pers. comm.).

These results were used to estimate DM digestibility of different pastures sampled from the three different farmlet management treatments. The digestibility scores of the calibration samples were entered into a spreadsheet template, which fitted a line of best fit; all equation details were then stored in a relational database maintained for all Cicerone Project data (Scott *et al*. 2013). Fitted regressions of observed digestibility scores against calibration samples of green and dead digestibility were used to predict average digestibility values from the average score recorded for each paddock.

The calibration equations for herbage mass and pasture quality over all 46 sampling dates from April 2003 to December 2006 showed high coefficients of determination. In general, the equations linking herbage mass were best met by quadratic equations whereas those for green and dead digestibility were best fitted with linear relationships. The R^2 values for the herbage mass calibrations were 0.98 (linear) and 0.99 (quadratic) with standard deviations of 0.02 and 0.01, respectively. For the calibrations of green and dead digestibility, the R^2 values for linear regressions were 0.93 and 0.88 with standard deviations of 0.07 and 0.12, respectively.

Pasture growth

Net pasture growth rate (NPGR) (kg DM/ha.day) represents the difference between pasture growth and decay (Anonymous 1993). In this study, NPGR was measured on three representative paddocks of each farmlet at approximately monthly intervals between June 2003 and February 2005. The changes in herbage mass over time were measured at three points within each of two grazing exclosure cages (Cayley and Bird 1991) positioned in each paddock at sites judged to be representative of the paddock in terms of herbage mass and composition (green and dead). It is acknowledged that using only two cages per paddock was well below the number of cages (~10) recommended by Cayley and Bird (1991) to reduce variability and sampling errors, especially in large and non-uniform paddocks (in terms of botanical composition); however, the number used was restricted due to resource limitations.

A falling plate (3-kg weighted disk mounted with a sliding tube and graduated measurement scale and a central rod to locate the ground surface) was used to provide a non-destructive, indirect calibrated measurement of the starting herbage mass on the three representative marked positions inside each cage at day zero (Cayley and Bird 1991). Five calibration cuts were taken outside each of the cages to establish a linear regression enabling calculation of the herbage mass at day zero. The intervals between the measurements in the grazing exclosure cages from the start (day_0) to the end (day_t) varied from 18 to 35 days, depending on the rate of pasture growth. At day_t, pasture cuts were taken from the three previously marked positions within each cage. The harvested material was oven-dried at 80°C for 48 h and the difference between the herbage mass on day_0 was subtracted from that on day_t and divided by the number of days.

Data from satellite (MODIS) images of NDVI (Donald *et al.* 2013) were used to provide regular weekly estimates of potential pasture growth rate over 5 large (250 by 250 m) pixels located within each of the farmlet boundaries. The pattern of these estimates of pasture growth enabled comparisons with the estimates of pasture growth obtained using grazing exclosure cages. More details of the use and value of these satellite images for understanding differences between the three farmlets have been provided in a related paper by Donald *et al.* (2013).

Weather

Over the course of the farmlet experiment, the weather experienced was generally drier-than-average with more frequent and severe frosting in winter compared with the 120-year climatic record. More details of the weather experienced and its relationship to these long-term climatic records have been provided in a related paper by Behrendt *et al.* (2013).

Statistical analyses

A discussion of the general approaches taken in the statistical analysis of data from this unreplicated farmlet experiment is the subject of a related paper by Murison and Scott (2013). The statistical analyses for this paper were conducted either directly using the statistical package R (R Development Core Team 2011) or with the software program Brodgar (version 2.7.2, Highland Statistics Ltd, Newburgh, United Kingdom), which links to R.

In general, the data presented here represent a large number of repeated-measures of a wide array of pasture characteristics from all paddocks of each of the farmlets in what was an agroecological study. As such, the observations were influenced not only by climatic and management treatments but also by the fact that they were taken from across a whole-farmlet trial with considerable variability. Thus, the statistical techniques employed were methods well suited to the analysis of data from ecological studies (Zuur *et al.* 2007). Curves were fitted using the locfit package (Loader 2010) of R, which selects a smoothed polynomial curve fitted to data points using locally weighted least-squares procedures.

All herbage mass, herbage quality and ground cover data were inspected first for the degree of correlation among the response and explanatory variables using Pair plots (Zuur *et al.* 2007). Both Generalised Linear Models (GLM) and Generalised Additive Models (GAM) were used to examine the factors that significantly affected the pasture characteristics as univariate analyses. Further, several Redundancy Analyses (Zuur *et al.* 2007) were carried out to explore the significance of the multivariate relationships between the response and explanatory factors, allowing the creation of correlation triplots (and biplots) and hence enabling a discussion of causal inference as described for this unreplicated experiment by Murison and Scott (2013).

The pattern of measured net pasture growth was explored with GLM analyses and regression against both weekly satellite (MODIS) images of greenness (NDVI) and growth indices (Fitzpatrick and Nix 1975) calculated using the long-term records for temperature and rainfall and shorter term records for radiation (Behrendt *et al.* 2013).

Results

Herbage mass

Table 1 shows the average total herbage mass recorded at the same times as the annual botanical composition assessments which were made in late summer of each year (Shakhane *et al.* 2013*a*). In March 2000, 4 months before the commencement of the farmlet treatments (1 July 2000), there was a large quantity of standing herbage mass (above 3500 kg DM/ha) due to little prior grazing with no significant difference ($P > 0.05$) between the farmlets (Table 1). The substantial decline in total herbage mass, which was recorded in both December 2002 and February 2003 (Table 1) reflected the effects of increased grazing and of a serious drought which constrained growth from early in 2002 to early 2003.

Fig. 1 shows details of the fitted curves, with 95% confidence intervals, of the monthly measurements of a wide array of herbage mass and quality attributes on the three farmlets from April 2003 to December 2006. Some obvious differences between farmlets can be readily observed from visual inspection of the figures. More details of the levels of significance between farmlets found from a series of GAM analyses, and the factors found to be significantly related to those differences, are presented in Table 2.

The range of factors explored include those linked to pasture renovation [pasture age (days since pasture renovation), proportion of C_3 species (Shakhane *et al.* 2013*a*), sowing phase (original or sown)], soil fertility (soil nitrogen, sulfur and phosphorus), stocking rate and grazing management (grazed proportion) over the 60 days before the sampling, climatic indices of light, temperature, soil moisture and growth, farmlet, paddock, date and several two-way interactions between date or farmlet with other factors (Table 2). Thus, the factors which comprised the farmlet treatments, namely different levels of pasture renovation (71% of the area of farmlet A and 8% of the area of each of farmlets B and C), different soil fertility levels and grazing management are captured by these factors. Grazing management is represented as a factor by the proportion of each farmlet grazed on any one day, which varied from ~0.4 to 0.6 on both farmlets A and B while on farmlet C the proportion grazed was generally well below 0.1. More details of these factors and their changes over time have been

Table 1. Total herbage mass (kg DM/ha), averaged across all paddocks of farmlets A, B and C over 3 years

Means followed by the same letter within each column are not significantly different (Waller–Duncan k-ratio *t*-test of Minimum Significant Difference (MSD) at $P = 0.05$)

Farmlet	March 2000	December 2000	December 2001	December 2002	February 2003
A	3708a	3574a	3229a	906b	808b
B	3552a	2664a	2918a	1935a	1471a
C	4548a	3599a	3101a	1901a	1276a
MSD	1488	1264	826	624	317

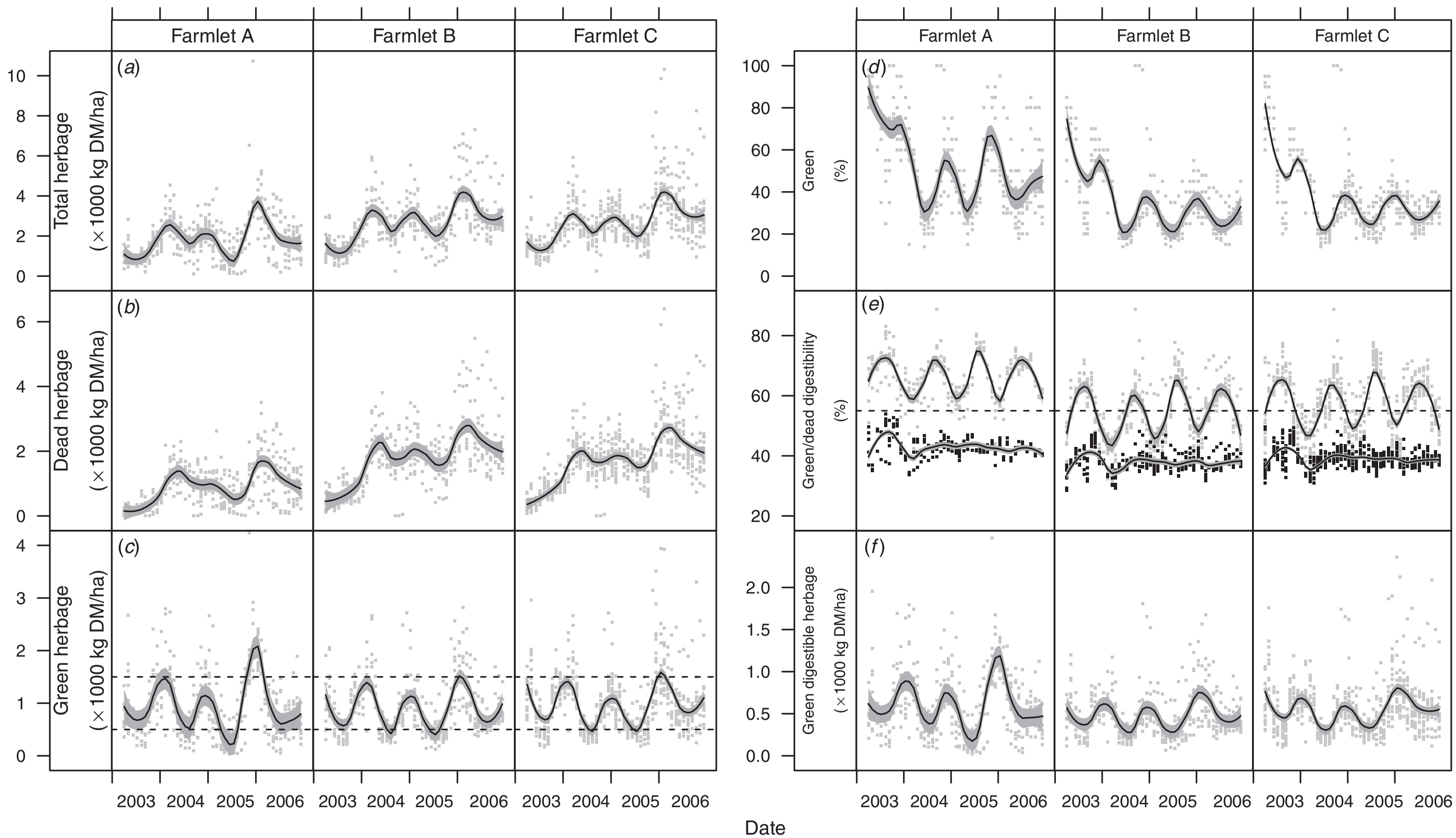

Fig. 1. Monthly measurements and fitted lines (by locfit [R] with 95% confidence intervals shaded) indicating changes in (*a*) total herbage, (*b*) dead herbage, (*c*) green herbage, (*d*) percent green, (*e*) green and dead digestibility and (*f*) green digestible herbage averaged across all paddocks of farmlets A, B and C from April 2003 to December 2006 inclusive. The dotted lines in (*c*) indicate levels of 1500 and 500 kg of green herbage whereas the dotted line in (*e*) shows the level of 55% digestibility, the level needed for animal maintenance.

Table 2. Levels of significance determined from Generalised Additive Model analyses of all measurements of pasture mass, quality, legume mass and ground cover on farmlets A, B and C from April 2003 to December 2006

Factors explored	Total herbage mass (TotHM)	Dead herbage mass (DHM)	Green herbage mass (GHM)	Green percent (GPct)	Green digestibility (GDig)	Dead digestibility (DDig)	Green digestible herbage mass (GDHM)	Legume herbage mass (LegHM)	Ground cover percent (GCPct)
Main effects									
Pasture age (days since sowing)	<0.001	n.s.	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	n.s.
Proportion C_3 species	n.s.	n.s.	n.s.	0.027	<0.001	<0.001	n.s.	n.s.	0.001
Soil nitrogen (N)	n.s.	n.s.	n.s.	n.s.	0.019	0.021	n.s.	n.s.	n.s.
Soil sulfur (S)	0.012	n.s.	0.006	n.s.	n.s.	n.s.	0.015	n.s.	n.s.
Soil phosphorus (P)	<0.001	0.003	0.001	n.s.	0.038	0.013	0.001	n.s.	0.005
Stocking rate (prior 60 days)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Grazed proportion (prior 60 days)	n.s.	n.s.	0.019	n.s.	n.s.	n.s.	0.029	n.s.	n.s.
Light index	<0.001	n.s.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Temperature index	<0.001	0.013	<0.001	<0.001	<0.001	n.s.	0.034	n.s.	n.s.
Soil moisture index	<0.001	<0.001	n.s.	<0.001	n.s.	<0.001	n.s.	n.s.	<0.001
Growth index	0.004	0.001	n.s.	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
Farmlet	<0.001	<0.001	0.002	n.s.	<0.001	<0.001	0.002	<0.001	0.003
Paddock	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Date	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001
Sowing phase	0.002	n.s.	<0.001	0.028	0.020	0.049	<0.001	<0.001	n.s.
Interactions (2-way)									
Date : proportion C_3 species	<0.001	<0.001	n.s.	n.s.	<0.001	<0.001	n.s.	n.s.	n.s.
Date : soil N	0.045	n.s.	n.s.	n.s.	n.s.	0.020	0.022	n.s.	n.s.
Date : soil S	<0.001	<0.001	n.s.	n.s.	n.s.	n.s.	0.008	n.s.	n.s.
Date: soil P	0.006	n.s.	<0.001	0.003	n.s.	n.s.	<0.001	n.s.	n.s.
Date : stocking rate (60)	<0.001	0.005	<0.001	n.s.	n.s.	n.s.	<0.001	n.s.	<0.001
Date : grazed proportion (60)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Farmlet : proportion C_3 species	<0.001	<0.001	<0.001	0.003	0.003	n.s.	<0.001	n.s.	<0.001
Farmlet : soil P	n.s.	<0.001	n.s.	0.001	<0.001	<0.001	n.s.	<0.001	n.s.
Deviance explained (%)	75.7	77.7	76.0	85.8	93.6	88.2	74.9	35.6	80.8

provided in a related paper on methods used in the farmlet experiment by Scott *et al.* (2013).

Regarding the fitted curves (Fig. 1), two aspects of these data are immediately obvious: first, there was a regular cyclical pattern between years, which was associated with season and second, there appears to be a large scatter of data points from individual paddocks. Typically, the lowest levels of herbage mass were recorded during the winter to early spring period while the largest values were in late summer. In spite of the apparent high degree of scatter, the small confidence intervals around the fitted lines confirmed a close correspondence among the data points from most paddocks within each of the farmlets; that is, the scattered points tended to be outliers. While the variability of the data points shows some extreme values for dead and green herbage (Fig. 1*b*, *c*) on farmlet A in late 2005, these were for one paddock, which was being saved for a silage harvest and which took place at the end of one favourable growth season (spring 2005), when substantially higher pasture growth occurred on farmlet A compared with farmlets B and C. No other opportunities for forage conservation occurred on any farmlet during the experimental period from July 2000 to December 2006.

Fig. 1*a* and *b* show that the total and dead herbage mass tended to be similar on farmlets B and C with both being somewhat higher than on farmlet A. Table 2 shows that the factors most strongly linked with these two attributes tended to be climatic and those with interactions with date or farmlet.

Fig. 1*c*, on the other hand, shows generally similar values across all farmlets for green herbage mass, derived from total herbage mass multiplied by percent green, a consequence of the generally higher levels of percentage green observed on farmlet A compared with the other two farmlets (Fig. 1*d*). In general, the three farmlets were found to have low levels of green herbage mass, generally well below 1500 kg/ha, especially in winter when at times the levels dropped below the 500 kg/ha of green herbage recommended as the minimum necessary for pregnant ewes (Bell 2003). The factors most strongly linked with green herbage were climatic and those connected with pasture renovation, soil fertility and grazing management (Table 2).

The high levels of percent green (Fig. 1*d*) on all farmlets in early 2003 reflect that, at that time, all pastures were showing early regrowth following a substantial rainfall event in February 2003 which ended a serious drought period which had extended from April 2002. In general, values of green herbage tended to be somewhat lower in 2004 and 2006, due to generally drier conditions in those years than in 2003 and 2005, which tended to be somewhat wetter years. More details of the climate experienced over the duration of the trial, which was found to have been drier-than-average, have been provided in a related paper by Behrendt *et al.* (2013). Percent green tended to be most strongly affected by climatic factors, pasture renovation with C_3 species and soil fertility (Table 2).

Pasture quality

The changes in pasture quality, shown as green and dead digestibility in Fig. 1*e*, demonstrate the significant and consistently higher levels of these two attributes on farmlet A compared with the other two farmlets. While the dead DM digestibility across the farmlets was always below that required for maintenance nutrition of ruminants (55%) (Langlands and Holmes 1978; Edwards 1981), the green DM digestibility of the pastures was at times well above that maintenance level with large differences between farmlets. In the case of farmlet A, green digestibility was almost always above the level needed for maintenance while the levels on both of the moderate-input systems (farmlets B and C) were commonly below that maintenance level, especially during summer and autumn (Fig. 1*e*).

Fig. 1*f* presents the product of green herbage mass and green digestibility, or green digestible herbage, which showed generally higher levels on farmlet A than on either of the other two farmlets. As can be seen in Table 2, the level of deviance explained by the significant main effects and interactions ranged from 88.2 to 93.6% for dead and green digestibility, respectively. The principal factors responsible for these differences in pasture quality were not only associated with climatic effects but also with differences in the level of pasture renovation, the proportion of C_3 species and interactions with soil fertility levels and grazing management factors.

Legume content

The monthly changes in the percentage of herbage mass attributable to legumes on the three farmlets from April 2003 onwards are shown in Fig. 2. It is clear that, although the levels of legume were generally quite low, given the generally drier-than-average seasons, they were especially low on farmlets B and C. In contrast, although the overall level of legumes recorded on farmlet A was generally less than 10%, it was substantially higher than on the two moderate input farmlets (B and C). The few records showing legume levels of up to 65% were recorded in the one paddock of farmlet A (A1), which had been sown to phalaris, chicory and lucerne, after the harvest of silage on that paddock. The factors most strongly linked to legume mass tended to be those associated with date, pasture renovation, soil phosphorus and the climatic factor, growth index (Table 2).

Ground cover

Fig. 3 shows the levels of ground cover recorded across all paddocks of the three farmlets from April 2003 onwards. The generally lower levels of ground cover up to 2004 reflect the fact that, from early 2003, all paddocks of all farmlets were recovering from a serious drought which had resulted in relatively low levels of ground cover for much of 2002, including early 2003. Nevertheless, ground cover across all farmlets was generally above the level of 70% below which runoff is much more likely to lead to erosion (Lang 1979). It is clear that, in general, farmlet A had lower levels of ground cover due in part to the higher stocking rate carried by that farmlet and to the higher number of renovated pastures compared with either farmlets B or C. The paddocks which had been recently renovated and the paddock from which silage had been harvested are indicated on Fig. 3. As shown in Table 2, the factors most strongly linked to ground cover were farmlet treatments, especially pasture renovation, climate and stocking rate.

Relationship between the response variables herbage mass, digestibility, legume mass, greenness (NDVI), ground cover and explanatory variables

Fig. 4 presents a biplot from a Redundancy Analysis between response variables relating to herbage mass, herbage quality, legume mass, ground cover and greenness (NDVI) and those explanatory variables found to be significant ($P < 0.01$). The sum of all canonical eigenvalues indicated that some 41% of the total variation in these data were explained by the significant relationships. This biplot shows many interesting relationships including: strong positive correlations between green herbage mass, green digestible herbage mass, NDVI and legume herbage

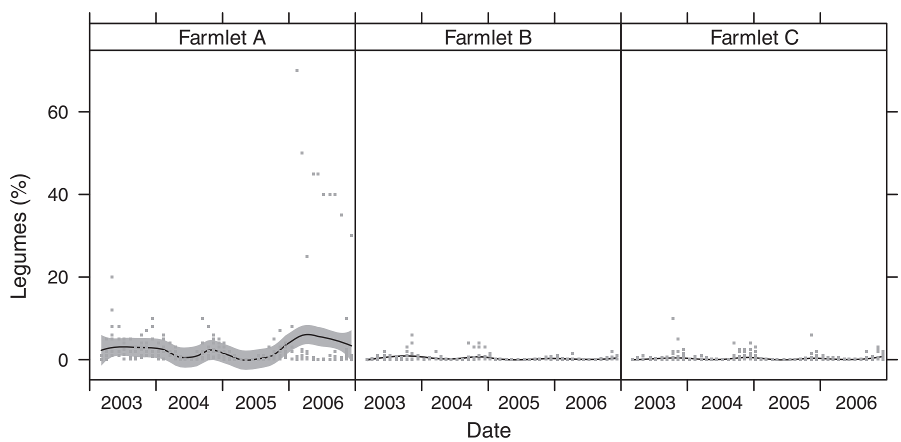

Fig. 2. Monthly measurements and fitted lines (by locfit with 95% confidence intervals shaded) indicating changes in percentage legume across all paddocks of farmlets A, B and C from April 2003 to December 2006 inclusive.

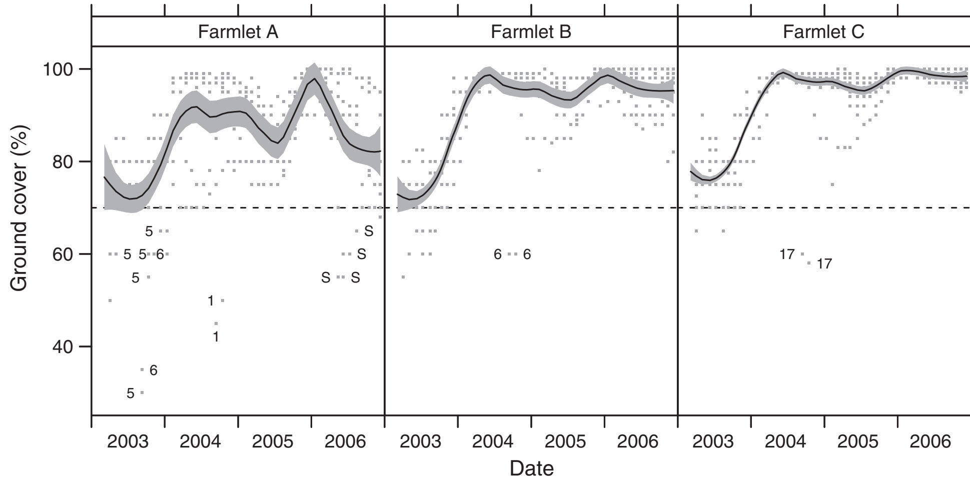

Fig. 3. Monthly measurements and fitted lines (by locfit with 95% confidence intervals shaded) indicating changes in ground cover assessed on each paddock of farmlets A, B and C from April 2003 to December 2006 inclusive. The dotted line indicates the 70% level of ground cover below which erosion risk is elevated. The data points labelled with numbers indicate paddocks which had been recently sown while those labelled 'S' indicate the paddock which had recently been harvested for silage.

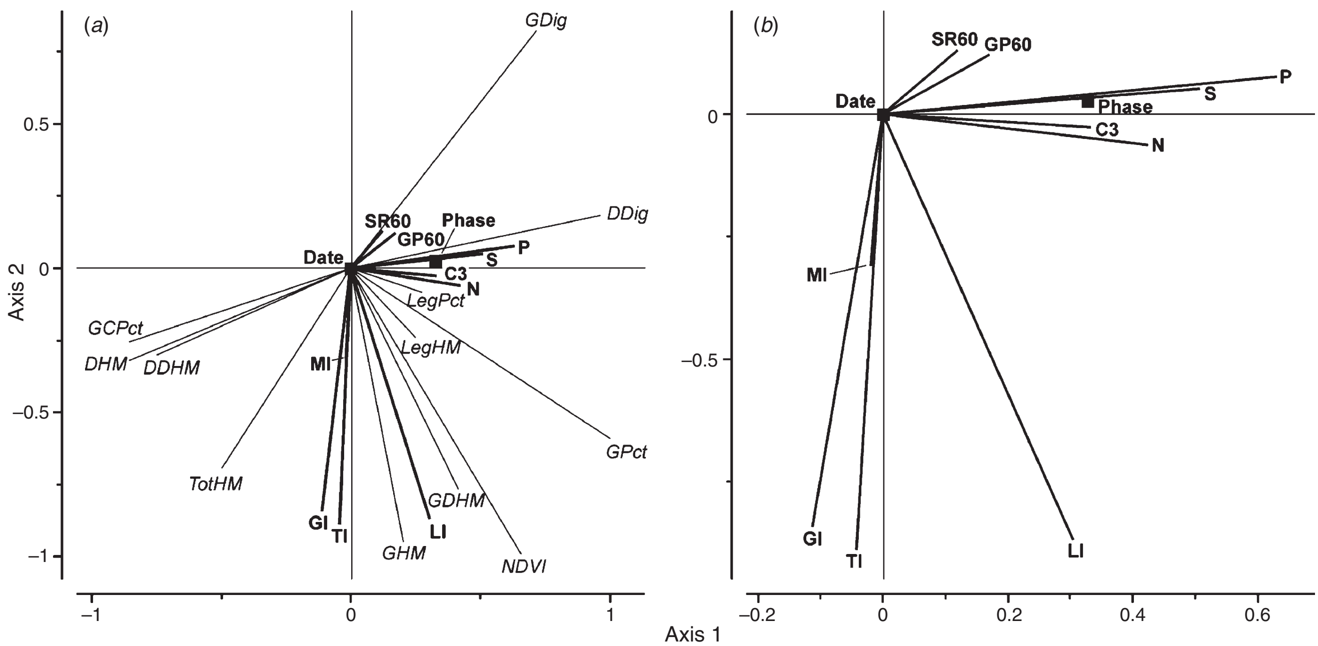

Fig. 4. (*a*) Biplot from multivariate Redundancy Analysis (RDA) showing relationship between response variables (thin lines) [total herbage mass (TotHM), dead herbage mass (DHM), dead digestible herbage mass (DDHM), green herbage mass (GHM), percent green (GPct), green digestibility (GDig), dead digestibility (DDig), green digestible herbage mass (GDHM)], MODIS normalised difference vegetation index (NDVI) and percent ground cover (GCPct) and significant explanatory variables (continuous variables: thick lines; nominal variables: ■) (stocking rate and grazed proportion over prior 60 days (SR60 and GP60, respectively), soil nitrogen (N), soil sulfur (S), soil phosphorus (P), proportion of temperate species (C_3), climatic indices of light (LI), temperature (TI), soil moisture (MI) and growth (GI), sowing phase (Phase) and date (Date). The relationships are explained more by axis 1 (46%) than by axis 2 (36%). (Acute angles between lines of variables indicate positive correlation whereas those close to 180° apart are strongly negatively correlated; angles of ~90° indicate variables which are not correlated with each other). Figure (*b*) provides a magnified view of the relationships among the explanatory variables shown also in (*a*).

mass with all four climatic indices, temperate (C_3) species and sowing phase; a positive correlation between percent green, dead digestibility and soil fertility; a positive correlation between green digestibility, stocking rate and grazed proportion; a positive correlation between ground cover and dead herbage mass and dead digestible herbage mass; a positive correlation between green digestibility and stocking rate and grazed proportion over the previous 60 days; and a negative correlation between green digestibility and dead herbage mass and dead digestible herbage mass. Of the explanatory factors, those which influenced the pasture characteristics most strongly (shown by the longest lines) were the climatic indices followed by soil fertility, temperate (C_3) species, sowing phase, grazed proportion and stocking rate.

Table 3 details the significant marginal and conditional effects from the redundancy analysis of the response variables related to herbage mass, quality, greenness and ground cover shown in Fig. 4.

Pasture growth rate

Fig. 5*a* shows the changes in measured net pasture growth rate, together with 95% confidence intervals, at approximately monthly intervals on three selected paddocks of each of the three farmlet systems from July 2003 to February 2005. While it is clear that growth was low on all farmlets during winter of 2004, the fitted curves show considerable short-term fluctuations typical of the stop-start conditions for growth experienced during much of the trial period. It also shows that a seasonal pattern in net pasture growth was observed with a consistent pattern of increased growth rate when season advanced from spring through summer and low growth rate mostly during winter even though the differences between farmlets were not statistically significant ($P > 0.05$).

A regression analysis between the response variable of measured net pasture growth rate against both date and weekly NDVI assessments [potential pasture growth rate, Donald *et al*. (2013)] from the MODIS satellite sensor as the explanatory variable showed that there was a significant relationship ($P < 0.001$) with both of these factors with an adjusted R^2 of 0.74. Thus, Fig. 5*b* displays the weekly fluctuations in NDVI observed on five MODIS pixels (250 by 250 m) on each of the three farmlets over the period from September 2003 to February 2005. More details concerning the value of satellite imagery for understanding pasture growth and botanical composition have been provided in a related paper by Donald *et al*. (2013).

Discussion

The changes in the accumulation of green, dead and total herbage mass reflect the effect of the seasonal and annual patterns of growth and senescence as well as the utilisation of the herbage mass by the livestock grazing the farmlets, which varied over time, both in number and physiological state (Hinch *et al*. 2013*a*). The low amounts of herbage mass in winter were associated not only with the increasing demand from pregnant ewes but also with the lower-than-average soil moisture and greater-than-average frost severity and frequency reported by Behrendt *et al*. (2013). As noted by Cook *et al*. (1978*a*), high utilisation rates in winter in this region can result in the displacement of high quality temperate (C_3) pasture species by less digestible warm-season (C_4) pasture species such as red grass (*Bothriochloa macra*), particularly under lower fertility conditions. In a related paper, Shakhane *et al*. (2013*a*) have shown such warm-season grasses did indeed increase within this farmlet trial over time, especially on the two farmlets with only moderate levels of soil fertility (farmlets B and C).

Farmlet A had consistently and significantly higher levels of digestibility for both the green and dead fractions than either of the other farmlets. Thus, it is clear that the quality of the diet on offer to grazing animals on this farmlet, through a combination of green herbage and digestibility (green digestible herbage) was higher than on either of the other farmlets, in spite of this farmlet (A) carrying a substantially higher stocking rate (Hinch *et al*. 2013*a*). The lower quality measured on both farmlets B and C was likely to be associated not only with the maturity of much of the higher quantity of dead herbage measured, but also with the lower levels of pasture renovation (8% of each farmlet's area over 6.5 years) (Scott *et al*. 2013) and soil fertility (Guppy *et al*. 2013) on these two farmlets.

The differences in total and green herbage mass between farmlets B and C were not significant. According to Hodgson (1990), high herbage mass, especially during late spring and early summer is associated with accumulated dead plant material reducing the digestibility and energy value of the herbage on

Table 3. Marginal and conditional effects of significant explanatory variables determined from redundancy analysis of response variables of herbage mass, herbage quality, greenness and ground cover shown in Fig. 4

Explanatory variables	Marginal effects		Conditional effects		
	Eigenvalue using only one explanatory variable	Eigenvalue as % (of sum all eigenvalues) using only one explanatory variable	Increase in the total sum of eigenvalues after including new variable	*F*-statistic	*P*-value
Light index	0.13	32.6	0.13	198.3	0.005
Sowing phase (original/sown) (Phase)	0.08	18.6	0.08	125.6	0.005
Temperature index	0.12	29.1	0.07	129.1	0.005
Date	0.05	11.5	0.04	81.7	0.005
Proportion of temperate species (C_3)	0.05	11.6	0.02	47.6	0.005
Stocking rate over previous 60 days (SR60)	0.01	2.6	0.02	33.8	0.005
Growth index	0.11	26.5	0.01	26.7	0.005
Moisture index	0.02	5.0	0.01	22.3	0.005
Soil phosphorus	0.08	18.8	0.01	16.7	0.005
Grazed proportion over previous 60 days (GP60)	0.01	3.5	0.01	11.4	0.005
Soil nitrogen	0.04	8.7	0.01	11.0	0.005
Soil sulfur	0.05	12.3	<0.01	3.7	0.01
Sum of eigenvalues	–	–	0.41	–	–

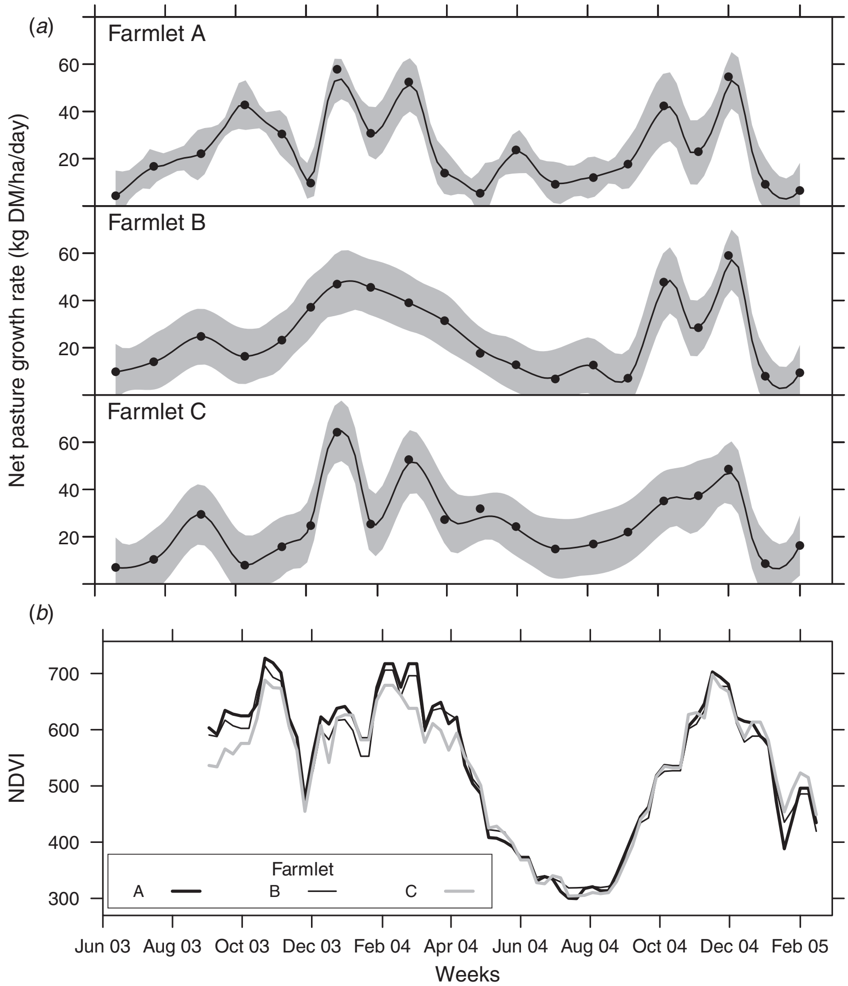

Fig. 5. (*a*) Measured net pasture growth rate (fitted by locfit with 95% confidence intervals) assessed on three paddocks of each of farmlets A, B and C using grazing exclosure cages from July 2003 to February 2005 and (*b*) weekly average NDVI values averaged over five MODIS pixels per farmlet indicating fluctuations in potential pasture growth rate on farmlets A, B and C from September 2003 to February 2005.

offer. The lower levels of green digestible herbage under these two moderate-input systems could also be attributed to the strong dominance of C_4 warm-season grasses (Shakhane *et al*. 2013*a*), as this pasture species group is characterised by short growing seasons and provides high-quality green herbage mass for only a limited period of the year (Cook *et al*. 1978*a*; Ayres *et al*. 2000).

It is clear that the biggest differences in herbage mass, and especially the green digestible portion were between the higher level of farmlet A compared with the two moderate input farmlets (B and C), regardless of their differences in grazing management. This is consistent with the findings of Waller *et al*. (2001) who reported that improving pastures and soil fertility had a far greater effect on herbage quality and livestock production than did grazing management. The effects of these differences in pasture mass and quality on animal production have been reported in related papers on liveweights (Hinch *et al*. 2013*a*), fat scores and reproduction (Hinch *et al*. 2013*b*) and wool production and quality (Cottle *et al*. 2013).

In spite of having set the objective of maintaining minimum critical levels of green herbage mass according to Prograze benchmarks (Bell and Allan 2000), too often it declined across all three farmlets to levels below 500 kg DM/ha, especially in winter, and thus was below the widely accepted benchmarks of 500–600 and 800–1000 kg green DM/ha for ewes in early and late pregnancy, respectively (Bell 2003). This highlights the challenges faced by livestock producers who, without detailed observational data, struggle to reach these benchmarks.

On the Northern Tablelands of NSW, Hamilton *et al*. (1973) showed that, when green herbage on offer drops below 550 kg DM/ha, sheep typically switch from green to dead herbage mass, which is of lower digestibility, resulting in a decline in nutrient intake and reduced animal performance such as lower liveweight gains and wool production (Hamilton 1975).

In addition to frequently being below the critical minimum of green herbage mass, it was also found that the maximum average level of green herbage mass attained was rarely at a level that would have ensured maximum weight gain per head. In research on the Northern Tablelands of NSW, Willoughby (1959) found an asymptotic relationship between animal liveweight gain and the availability of green pasture at levels above 1570 kg green DM/ha. Penning *et al*. (1994) concluded similarly, reporting that maximum intake per animal was reached at ~1500 kg green DM/ha. Thus, it appears likely that the level of green herbage within this farmlet trial generally constrained liveweight gain well below maximum growth rates.

The generally low levels of legume on the farmlets over the duration of the experiment were also likely to have restricted potential animal production as grazing ruminants have a partial preference for selecting clover compared with grass up to the point where ~50% of a pasture comprises legume (Chapman *et al*. 2007). It may be that the low presence of legume was due to it being consumed soon after becoming available as has been previously suggested by McCaskill and Blair (1988), particularly in dry seasons.

Changes in herbage digestibility not only interact with changes in herbage mass, but are also directly related to pasture growth as was found in this study. Related papers have demonstrated links between pasture characteristics and other parameters. For example, Donald *et al*. (2013) found a significant positive correlation between remotely sensed images of greenness (NDVI), which is related to potential pasture growth rate, and the proportion of sown perennial grasses and legumes, which were higher on farmlet A compared with the other two farmlets (Shakhane *et al*. 2013*a*). Further, analysis of the botanical composition of the pastures showed farmlet A to have a greater proportion of sown, introduced and C_3 species than the other farmlets (Shakhane *et al*. 2013*a*). Also, Guppy *et al*. (2013) reported a significant positive correlation between soil phosphorus and the proportion of legumes, cool season annual/biennial grasses and sown perennial grasses which again were at higher levels on farmlet A.

The lower levels of accumulated dead herbage mass on farmlet A suggests less wastage of herbage through senescence. On the other hand, the accumulation of surplus herbage found on farmlets B and C resulted in carry-over of dead residual material, which can make it more difficult for a grazing animal to select a diet of sufficient quality. The fact that farmlet A showed significantly higher herbage quality than farmlets B and C, even though the grazing management on A and B was the same, confirms the substantial influence of the combination of higher soil fertility levels, the sowing of temperate pasture species and the higher stocking rate on enhancing pasture quality, as found by others (Saul *et al*. 1999). This is likely to be the principal reason that farmlet A was able to support more stock without penalties in per head performance over a period of several years even though, at times, more supplement was needed on this farmlet (Hinch *et al*. 2013*a*).

Although the limited number of measurements of pasture growth using grazing exclosure cages found no significant differences between farmlets, a related paper by Donald *et al*. (2013) demonstrated significant differences over time between farmlets in potential pasture growth rate as assessed by remotely sensed images. These estimates were based upon Landsat satellite images of greenness (NDVI), taken in spring of each year, over more than 2500 sampling points (each 25 by 25 m), across all paddocks of the three farmlets. Thus, as would be expected in view of the higher stocking rate supported over time by farmlet A (Hinch *et al*. 2013*a*), the NDVI data suggest that potential pasture growth was indeed significantly higher ($P < 0.05$) on farmlet A compared with farmlet C, which was higher than farmlet B (Donald *et al*. 2013). It may be that, especially on farmlets A and B, where a greater proportion of these farmlets was grazed at any one time, that the greenness detected may have been an underestimate of potential pasture growth; as noted by one respondent to a survey of graziers by O'Keeffe (1992), especially relating to periods of low growth, 'you don't really know how much pasture you grow because the animals keep eating it'. It is noteworthy that this satellite technology was also able to detect differences in botanical functional groups, soil type boundaries and recent grazing activity (Donald *et al*. 2013).

Control over the quantity and quality of food ingested by grazing ruminants in temperate pasture systems remains elusive due in part to the ability of grazing animals to make foraging choices from communities of mixed plant species. Grazing behaviour and intake interact strongly with the feed supply-demand balance, pasture composition, and grazing method (Chapman *et al*. 2007). The challenge for grassland management is to present feed to animals at pasture in ways that allow them to meet their dietary preferences, while also allowing high rates of animal production per hectare (Chapman *et al*. 2007). Estimates of the balance between feed supply and animal demand on this farmlet experiment have been examined in a related paper by Shakhane *et al*. (2013*b*).

The large differences in graze and rest period achieved on the three farmlets, reported by Hinch *et al*. (2013*a*), showed that both farmlets A and B had similar but relatively long graze periods (30–100 days) interspersed with relatively short rest periods (of ~50 days), whereas farmlet C had short graze periods (2–10 days) with extended rest periods (60–200 days). The relationship between dietary intake and grazing management has been explored for cattle by McCollum *et al*. (1994) who found, in a comparison of short-duration grazing with different graze and rest periods, that diet composition had a higher, more stable plane of nutrition when grazing periods were more frequent compared with slower rotational grazing.

The influence of the higher level of soil fertility and pasture renovation on farmlet A on the level of digestibility of the herbage was substantial and is consistent with the findings from a long-term experiment in western Victoria (Saul *et al*. 1999). They found that high rates of fertiliser (up to 33 kg/ha of phosphorus) were responsible for significantly increasing the digestible DM of the clover and volunteer components of the pasture and noted the importance of monitoring nutritive value because of its substantial flow-on effects for animal production per head and per hectare.

The competing influences of the seasonal pattern of pasture growth and herbage defoliation by grazing animals determines that total herbage mass is at a maximum level in spring–summer and declines over summer–autumn to reach a minimum level from mid winter (McPhee *et al*. 1997; Ayres *et al*. 2001). Generally, on the Northern Tablelands, the availability of green herbage mass is high in summer due to warm-season growth and low in winter due to the consumption of feed by animals and the effects of severe frosting causing leaf senescence (Ayres *et al*. 2000).

While the generally low rates of pasture growth observed on the three farmlets can largely be attributed to the climatic conditions, it is likely also that the low levels of green herbage mass also contributed to the low growth rates. As noted by Harris (1978), following defoliation, regrowth is influenced by the amount of residual green leaf, the rate of recovery of root growth and the quantity and activity of meristem tissues remaining.

Accurate measurement of pasture growth rate in the present study proved to be difficult. Several factors contributed to the high variability between the paddocks. Most importantly, the three paddocks chosen for study within each farmlet were deliberately chosen to be representative of the variation among paddocks; thus, considerable variability was embedded in the inter-paddock variability that was a feature of each farmlet. While this meant that the paddocks were representative of the farmlets, it made it more difficult to obtain statistically significant differences between the farmlets. Further, the falling plate is best suited to even ground and pastures without large differences in height over short distances, such as the frequent, tall, grass tussocks encountered within this farmlet experiment. Limited financial and technical resources also meant that only small numbers of grazing exclosure cages were able to be used. This, combined with the small proportion of each paddock sampled, contributed to the high variability of the growth rate measurements.

As noted by Saul and Chapman (2002) there are trade-offs when managing soils, pastures and grazing animals. Thus, the balance between legumes and grasses and between livestock production on a per head and a per hectare basis are affected by management systems. They noted the need for long-term studies of the complex interactions involved as it can take many years for stable pasture compositions to develop. Unfortunately, given that the climatic conditions experienced within this farmlet trial were mostly drier-than-average, it has not been possible to fully resolve these complex interacting factors.

Nevertheless, it is noteworthy that the multivariate approach described by Zuur *et al*. (2007), which we have used to analyse many of the complex interacting factors, assisted by confirming the significance of the many effects and complex interactions described above, within this unreplicated, whole-farmlet experiment. Thus, the complex of pasture supply attributes of various components of herbage mass and quality, of ground cover and greenness comprised the response variables of major interest in this paper. Consistent with the above discussion of factors affecting herbage mass and quality, it has been confirmed that, of the many significant explanatory factors associated with changes in the response variables, those most responsible were in declining order of importance: those related to season and weather (light, temperature, growth and moisture indices; date), pasture renovation (sowing phase and C_3 species), grazing management (stocking rate and grazed proportion) and soil fertility (phosphorus, nitrogen and sulfur). This confirms the utility of the multivariate approach taken as it permitted the teasing apart of significant relationships, or causal inference (Murison and Scott 2013), from complex agroecological datasets such as those accumulated over the course of this grazed field experiment.

This paper has provided extensive evidence of the differences which developed between the three farmlets after the management treatments took effect. The fact that the largest differences were between farmlet A and the other two farmlets, both of which were similar in all respects reported here, supports the view that it was the greater levels of pasture renovation and soil fertility (farmlet A) that led to significantly higher levels of green digestible herbage and legume mass compared with typical management (farmlet B) while intensive grazing management (farmlet C) had little effect on the pasture characteristics reported here.

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