CSIRO PUBLISHING

Animal Production Science, 2013, **53**, 649–657
http://dx.doi.org/10.1071/AN12147

Whole-farm management of soil nutrients drives productive grazing systems: the Cicerone farmlet experiment confirms earlier research

C. N. Guppy[A,C], *C. Edwards*[B], *G. J. Blair*[A] *and J. M. Scott*[A]

[A]School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia.
[B]NSW Department of Primary Industries, Armidale, NSW 2351, Australia.
[C]Corresponding author. Email: cguppy@une.edu.au

Abstract. The Cicerone Project included a study of three 53-ha farmlets, each subjected to a different management system. The systems varied first in their input of fertilisers and sown pastures and second in their grazing management. Farmlet A undertook a high level of pasture renovation and had soil fertility targets of 60 mg/kg Colwell phosphorus (P) and 10 mg/kg KCl-40 sulfur (S), while farmlets B and C both had a low rate of pasture renovation and targets of 20 mg/kg P and 6.5 mg/kg S. In addition, both farmlets A and B adopted a flexible rotational grazing regime over the eight paddocks of each farmlet, whereas farmlet C, which had 37 paddocks, adopted intensive rotational grazing.

This paper first reviews the literature relating to soil fertility research in the summer-dominant rainfall region of the Northern Tablelands of New South Wales, Australia. It then examines whether the soil fertility targets set for the farmlets were attained and how the consequences of fertiliser management measured in this trial related to earlier research findings.

Fertiliser applications, comprising both capital and maintenance rates, were based on soil test results but at times were constrained by the availability of finance. Soil tests over 5 years indicated that only nitrogen (N), P and S varied with time within the farmlets while the other indices of soil fertility remained similar. Phosphorus and S levels increased in response to fertiliser applications whereas N levels responded to increases in legume composition, which was stimulated by the higher P and S levels. Multivariate statistical analyses demonstrated that farmlet productivity was driven by P and S fertility and thus the two farmlets with lower P and S fertility (farmlets B and C) had similar but lower levels of farmlet productivity compared with farmlet A. Significant increases in several measured pasture productivity parameters were observed in response to the higher P and S fertility on farmlet A, especially when climatic conditions were favourable. The results of the Cicerone farmlet experiment confirm the findings of earlier research on the Northern Tablelands, and elsewhere in the high rainfall zone, that has demonstrated that higher soil fertility levels and pasture renovation enhance the productivity of grazing enterprises more than grazing management, without imposing significant risks to the environment.

Additional keywords: fertiliser management, Northern Tablelands, pasture response, phosphorus, sulfur.

Received 27 April 2012, accepted 13 March 2013, published online 10 July 2013

Introduction

Soil fertility is critical to productive pasture-based livestock systems and this manuscript outlines the importance of soil fertility within the Cicerone farmlet experiment, which is the primary focus of this Special Issue. The soils of the Northern Tablelands of New South Wales (NSW), Australia, were nutrient poor when grazing enterprises began in 1832; this constrained production through to the 1930s when applications of single superphosphate (SSP) with white clover (*Trifolium repens*) commenced, leading to dramatic increases in productivity (Robinson and Lazenby 1976). This is highlighted in data presented by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and NSW Agriculture (CSIRO 1964) and a more recent review indicating that at least 70% of soils in the southern portion of the Northern Tablelands were moderately or severely deficient in phosphorus (P) and/or sulfur (S) (Edwards and Duncan 2002) based on critical values of 30 mg/kg for P (Colwell 1963) and 6–8 mg/kg for S (Blair *et al*. 1991).

Soil fertility and pasture research on the Northern Tablelands of NSW has had a relatively long history. The addition of white clover, together with SSP, has been, and remains, the backbone of pasture development and livestock production in the region. Being a perennial legume, white clover provides most of the nitrogen (N) inputs required to produce protein products such as meat and wool. The importance of sown pastures and fertiliser application has been previously demonstrated in a 3-year grazing study (CSIRO 1964) where wool production increased by 0.11 kg/ha for every 1% increase in improved pastures. Robinson and Lazenby (1976) found, in a 5-year study, that animals on fertilised pastures were 15% heavier and produced 18% more wool than those on unfertilised pasture. The combination of fertiliser and higher stocking rate (SR) increased wool production by 49%. Thus, it has long been recognised that phosphate fertiliser, which promotes increased N fixation by legumes such as white clover, has positive flow-on effects for grass growth, pasture quality and animal production (Robinson and Lazenby 1976; Clark 2010).

Grazed experiments investigating the effects of fertilisers on pastures and livestock ideally need to allow for both developmental and maintenance rates of fertiliser to be used over sufficient years to enable different treatments to reach 'steady-state' levels, especially as there can be complex effects on botanical composition and animal production (Morley and Spedding 1968).

The purpose of this paper is to summarise the changes in soil fertility observed over time across all paddocks of three farmlets, detail the strategies employed to fertilise to specific fertility targets and gain some understanding of the dynamics of each farmlet with respect to soil fertility and its relationship with pasture and animal production. The risk of P movement through runoff into waterways is also examined using a published risk-assessment approach. This paper describes and explores the changes in soil nutrient levels that were found to be associated with enhanced pasture nutritive value (Shakhane *et al*. 2013*a*) that supported higher SR (Hinch *et al*. 2013*a*) within the Cicerone farmlet experiment. Where appropriate, reference is also made to other manuscripts within this Special Issue relating to pasture growth and quality, sheep liveweight, reproduction, wool production and quality and the economics of fertility management.

Methods

The Cicerone Project's farmlet study was conducted at the CSIRO McMaster Research Laboratory 'Chiswick', some 18 km south of Armidale, NSW (latitude: S30.52, longitude: E151.67). In response to the research needs of livestock producers of the region, identified by Kaine *et al*. (2013), the study aimed to explore how whole-farm sustainability and profitability are affected by different levels of pasture inputs and by intensive rotational grazing. The selection of the treatments (Scott *et al*. 2013*c*) and the conduct of the Cicerone farmlet experiment were under the control of a management Board consisting of a majority of local livestock producers with extension, research and consultant specialists, which met at ~6-week intervals throughout the Project. Prior to the commencement of the different management strategies, the land was partitioned among farmlets in such a way that each unreplicated farmlet was allocated areas with equivalent attributes such as soil type, slope and fertiliser history (Scott *et al*. 2013*d*). Soils were mostly a mix of Yellow Chromosol and Sodosol derived from granite parent material with a minority of Brown Dermosols derived from basalt (Isbell 1996). A full description of Chiswick Research Station soils can be found in Schafer (1980) while the distribution of soil types across farmlets can be found in a related paper by Scott *et al*. (2013*d*). No soil samples were taken in 2000 before the commencement of the treatments, as the primary determinant of the land allocation to farmlets was soil type, slope and elevation. About 15% of the land used for the Cicerone farmlet experiment had previously been used in a study of natural and improved pastures (K. King, pers. comm.). Soil samples taken in 1987 showed Colwell P of unfertilised native pastures was ~21 mg/kg while fertilised portions were 80 mg/kg. In 2001, soil samples were taken from two paddocks in each farmlet, 2002 from 26 paddocks and from all main paddocks in all farmlets in 2003, 2005 and 2006 (farmlet A, eight paddocks; B, eight paddocks; C, 17 paddocks). Grid sampling procedures were used and all samples bulked and analysed by the Incitec Pivot soil testing service.

The eight paddocks allocated to farmlet A were managed under a higher input management strategy (in terms of soil fertility and pasture renovation) with a goal of eventually supporting a SR of 15 dry sheep equivalents (dse)/ha. The eight paddocks allocated to farmlet B were managed under a medium input strategy with a SR goal of 7.5 dse/ha. Farmlet C was managed under the same medium input strategy as farmlet B, but it was subdivided into 37 paddocks to allow intensive rotational grazing; this farmlet aimed at eventually supporting a SR of 15 dse/ha. More details of the farmlet trial and the choice of treatments have been provided by Scott *et al*. (2013*c*). Thus, direct comparisons could be made between farmlets A and B in terms of levels of input, and between farmlets B and C in terms of grazing management.

The rainfall and climate experienced over the 6.5 years of the trial has been summarised in Behrendt *et al*. (2013*b*). In brief, the trial experienced below-median soil moisture conditions over most of the trial period and more frequent severe frosts during winter of the majority of years, thus constraining the responses to the farmlet treatments.

Soil fertility targets

Following allocation of paddocks to each of the farmlets, differential fertiliser application rates were commenced from July 2000. Initially, the farmlet guidelines chosen by the Cicerone Board (Scott *et al*. 2013*c*) were to strive for what was judged by the Board to be a 'maintenance' application rate of fertiliser for farmlets B and C equivalent to 125 kg/ha. year of SSP applied to one-third of all paddocks on those two farmlets, with some soil tests to be conducted regularly. In contrast, the aim of the higher input system (farmlet A) was to allow an increase in soil P and S, to be verified through soil testing, by the application of 250 kg/ha.year of SSP to all paddocks on farmlet A.

These guidelines were modified in 2001 when a decision was taken, on advice from the authors, to assess soil fertility annually within all paddocks of all farmlets. At this point, the guidelines were altered so that fertiliser would be applied differentially among paddocks in order to achieve specific soil fertility targets of P and S levels within each paddock of each farmlet.

The soil P and S levels were measured using the Colwell P method (Colwell 1963) and the KCl-40 S test (Blair *et al*. 1991).

Both of these soil tests give an estimate of the level of available P and S to pasture systems and have been calibrated for the Northern Tablelands and critical concentrations determined (Holford and Crocker 1988; Blair *et al*. 1991). The maintenance applications of farmlets B and C were set such that they were likely to still be responsive to P and S applications, while farmlet A was designed to achieve >90% of potential pasture production in the region. The target soil P and S levels of farmlet A (higher input) were 60 and 10 mg/kg, respectively [~50% higher than critical response levels suggested by Colwell (1963) and Blair *et al*. (1991)]. For farmlets B and C the target P and S levels were set at 20 and 6.5 mg/kg, respectively. Target levels on farmlets B and C were typical of the region with respect to P but below recommended levels by ~15–20%, while S levels were at critical levels. In addition, on the 'higher input' farmlet (A), it was agreed that additional nutritional strategies could be implemented if warranted. For example, the aim on this farmlet was to encourage biological N fixation, through sowing and fertilising, via moderately high legume content (i.e. up to 30% of feed on offer). To this end, applications of molybdenum were to be permitted if the legume percentage was inadequate. In addition, moderate levels of N fertiliser were to be allowed if they were judged necessary to differentially enhance the growth of establishing perennial grasses over volunteer annual grasses or to increase autumn–winter production, provided that application rates did not lead to declines in the percentage of legumes.

Fertiliser management

To adjust soil P and S status to achieve target levels for each of the paddocks in each farmlet, soil tests were examined each year and individually tailored fertiliser strategies were developed for each paddock. For example, on farmlet A, if a paddock had soil P of 45 mg/kg and soil S of 12 mg/kg, fertiliser recommendations were made to apply fertiliser that was high in P but low in S, such as triple superphosphate. However, where both soil P and S were low, then fertilisers that contained both were applied, such as SSP. If P was adequate but S low, then an S-fortified SSP product (e.g. SF45, Incitec Pivot Ltd, Geelong, Vic.) was applied. The rates at which fertilisers were applied corresponded with maintenance levels [calculated as 1.1 kg P/dse.ha per year (M. Duncan, pers. comm.)] plus an additional P application based on previous research (G. J. Blair, unpubl. data) to increase the Colwell soil P status by 0.15 mg/kg P applied/ha. year for lower P additions. Budget limitations in the latter years of the Cicerone Project resulted in minimal fertiliser inputs being applied in those later years, in spite of recommendations, resulting in some declines in soil test values below target levels over the years of 2005 and 2006.

Soil chemical analyses

Commercial soil tests on soil samples included pH, EC, exchangeable cations [$cmol^{(+)}$/kg], available P and S (mg/kg), chloride (mg/kg), and, in later years, organic carbon (C, %). As this paper seeks to examine trends in soil P and S status over time, graphical presentations of the data focus on changes in fitted values of these two nutrient elements. Other soil values remained unchanged over the 5 years of sampling and are not focussed on in this paper (data not shown).

Outliers in P and S values were determined by visual inspection of the data. If results were dramatically higher or lower than anticipated, fertiliser and paddock history were investigated to identify causes for the deviations. For example, the P status of paddock B6 in 2005 was 5 times higher than other paddocks on that farmlet. Investigation revealed it had been recently re-sown and fertilised and hence the sample could have been affected by contamination with fertiliser residues; hence it was excluded from the calculations. Only 2 of 105 samples were thus excluded. Climatic data (rainfall and average temperature before sampling) were taken into consideration to aid in the interpretation of soil fertility trends over the 6.5 years of the trial.

Environmental risk assessment

The risk of environmental degradation following increased nutrient inputs and changed grazing management was assessed using the Farm Nutrient Loss Index (FLNI) developed by Melland *et al*. (2004). The FLNI uses source and transport factors to estimate risk of P or N loss off-farm. The source factors used in farmlet modelling included soil test values, fertiliser rates and timing of application, nutrient 'hotspot' estimation, pasture type, ground cover and SR. Transport factors included surplus water (an estimate of runoff based on climatic region), soil type, slope and land shape, ground cover, pasture type and proximity to waterways. These were then weighted to estimate the risk of nutrient loss on a scale of 1–8.

Statistical analyses

The statistical approaches to analysing unreplicated field studies such as this farmlet experiment have been discussed in relation to the literature in a related paper by Murison and Scott (2013). Soil P and S levels were examined using a linear fixed effects model fit by REML to account for the randomness of paddock selection for soil sampling within each farmlet. As trends in both soil P and S were variable over time, they were summarised with the use of the R (R Development Core Team 2011) package 'locfit' thus fitting smoothed curves with confidence intervals which employ local regression using log-likelihood criteria around each point.

Pairplots (Zuur *et al*. 2007) were used for exploratory data analysis to examine the degree of correlation between a wide array of response and explanatory variables using the software program 'Brodgar' (version 2.7.2, Highland Statistics Ltd, Newburgh, UK), which provides an interface to the statistical package R (R Development Core Team 2011). Data were analysed using a range of univariate and multivariate techniques using 'Brodgar' and, where appropriate, the normality of the data were examined using QQ plots. Both a generalised linear model and a generalised additive model were tested but both were found to suffer from non-normality in the data. Multivariate redundancy analyses (RDA) (Zuur *et al*. 2007), an extension of Principal Component Analysis, were used to explore the data for significant relationships between response variables as a function of explanatory variables, especially given that normality of data is not a requirement for such analyses (Zuur *et al.* 2007).

Results

Fertiliser applied

Fig. 1 shows the average cumulative amount of fertiliser nutrients applied per hectare over the course of the farmlet trial. Farmlet A received substantially more P and S than farmlets B and C, both of which received considerably lower but similar levels. The average annual rate of fertiliser nutrients applied shows that, while farmlet A received some 13.1 kg P/ha.year, the rate for farmlets B and C were 4.9 and 4.3, respectively. Sulfur was applied at average annual rates of 10.2, 5.1 and 4.0 to farmlets A, B and C, respectively. Although farmlet A also recorded higher average annual rates of N and potassium, these were generally low rates and were used only during the pasture establishment phase. The slightly lower average annual rates applied to farmlet C compared with farmlet B reflect the fact that farmlet C had slightly, but not significantly, higher soil test values for P and S over most sampling times (Fig. 2) thus requiring smaller applications to maintain the target levels.

Soil chemical fertility

Target fertility levels were met in 3 of the 5 years that soil sampling was undertaken, except for farmlet A in 2001 before the capital P application (Fig. 2). In the last 3 years of the experiment fertility levels declined and in most cases did not meet the target soil test levels. This decline coincided with a lack of project finance for fertiliser.

Environmental assessment

The farmlets were analysed for environmental risk using the FNLI developed for grazing systems and calibrated for the Northern Tablelands region of NSW. Farmlet A, despite having higher Colwell P status, was assessed as having a low risk with respect to environmental flows of P off-site (risk

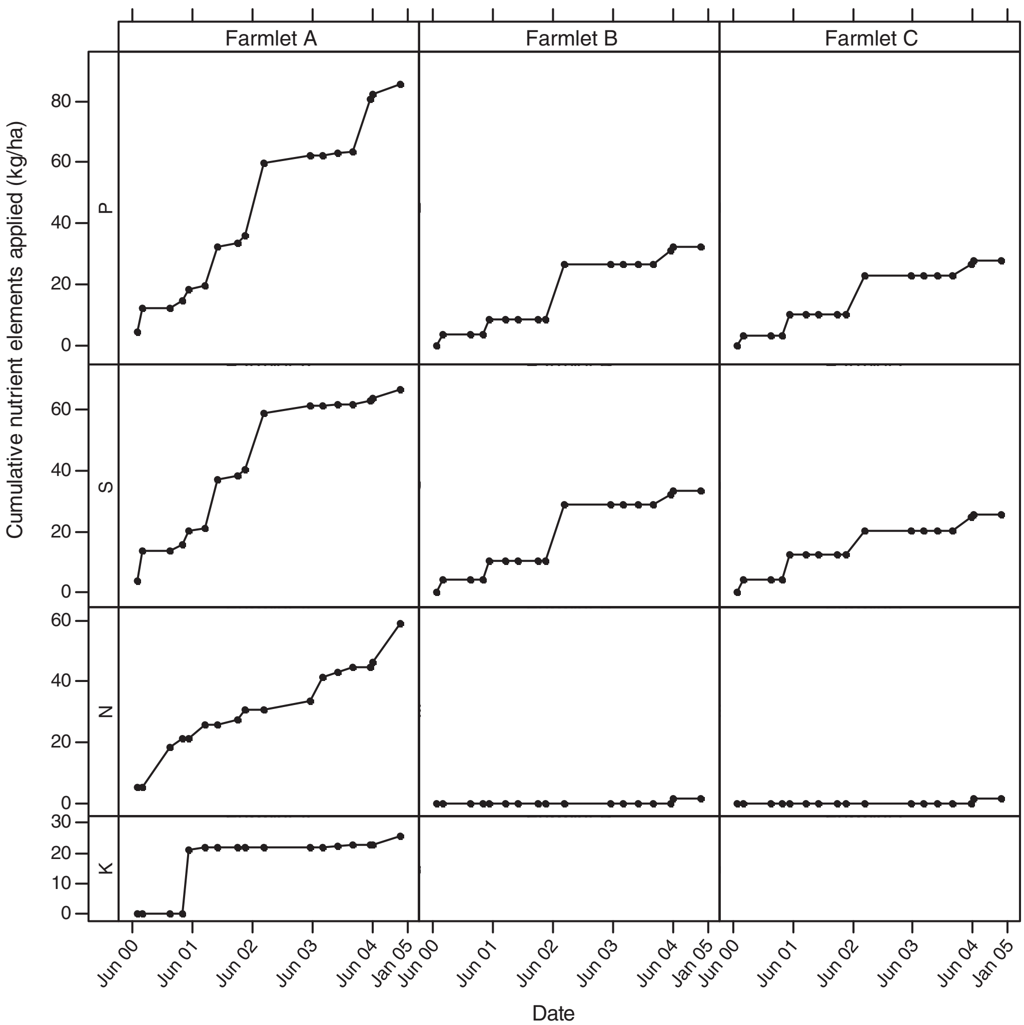

Fig. 1. Average cumulative sum of nutrients (kg/ha) applied as fertiliser to paddocks of farmlets A, B and C over the period June 2000 to December 2006 (Scott *et al.* 2013*c*). Note that no additions of fertiliser were made beyond summer 2005.

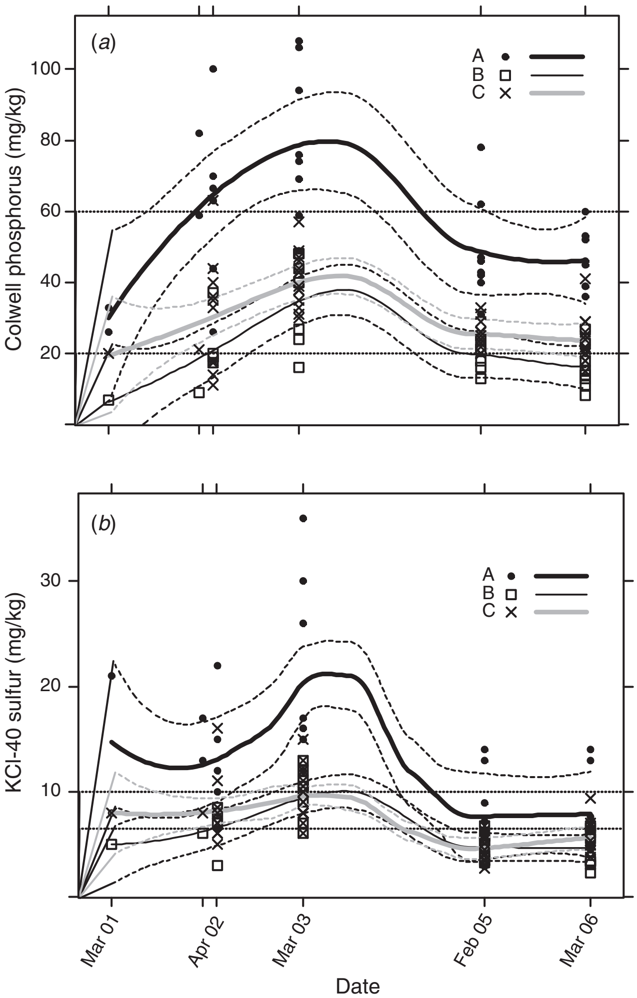

Fig. 2. Trends in (*a*) soil phosphorus (Colwell P) and (*b*) soil sulfur (KCl-40 S) levels on the three farmlets from March 2001 to March 2006 showing fitted lines and 95% confidence intervals estimated using local regression, likelihood and density (locfit). Target soil P and S levels for farmlet A (60 and 10 mg/kg, respectively), and farmlets B and C (20 and 6.5 mg/kg) are indicated on the figures by the horizontal dotted lines.

rating of 2 on scale of 1–8). Farmlets B and C were also low risk, as P inputs were lower than on farmlet A (Fig. 1).

Relationships between soil nutrient levels and fertiliser applications

Fertiliser application was most strongly correlated with Colwell P ($r = 0.61$) followed by nitrate-N (0.41) and sulfate-S (0.40). Correlations with pH and organic C were not significant (data not shown). The creation, maintenance and decline of different soil P and S levels between the farmlet treatments are portrayed in Fig. 2, which shows the net effects of the different rates of increase of soil P and S combined with the multiple factors known to cause decreases in soil P levels, such as the effects of soil reactions and product removal over time. While the fitted curves for farmlet A for P and S are well above those for the other two farmlets, which are not significantly different from each other, it is noteworthy that the shape of the fitted curves are all similar. All three curves show increases to the point where fertiliser application rates slowed and thereafter, declined to lower levels which tended to be asymptotic to the *x*-axis. These rates of decline are consistent with the shape of residual soil fertility curves described by others (Barrow and Carter 1978; Goh and Nguyen 1992).

Relationship between soil nutrient levels and production parameters

There was a high Pearson correlation coefficient between SR (Hinch *et al*. 2013*a*) and legume DM (0.56) while legume DM was most positively correlated with P (0.62), N (0.55) and S (0.49), respectively. As soil N was found not to be significantly correlated with N fertiliser applications [less than 60 kg N/ha was applied during the entire experiment, and all of that was on farmlet A (Fig. 1)], it is concluded that the increased soil N observed on farmlet A was associated with the significantly increased levels of legume herbage on that farmlet (Shakhane *et al*. 2013*a*).

A RDA was conducted on those pasture response variables which were found to be most significantly related to livestock production (Hinch *et al*. 2013*a*), namely green digestible herbage (GreenDDM), dead digestible herbage (DeadDDM), legume herbage (LegumeDM) and the emergent property of SR. The relationship of these response variables to the explanatory variables of Date, soil N, P and S and grazed proportion [the proportion of each farmlet grazed at any one time (GP)] are shown for two periods between three soil testing dates (March 2003–February 2005 and February 2005–March 2006) using soil test data collected at the beginning of each period. Initially, all soil test data were included but later non-significant terms (pH, organic C and paddock) were removed from the analyses. In order to remove some of the complexity of data presentation, due to high co-linearity, total herbage, dead herbage and green herbage were removed from the response variables to leave GreenDDM, LegumeDM and DeadDDM along with SR as the response variables. Total eigenvalues were 0.46 suggesting that soil nutrients and date significantly explained some 46% of the variation in these data (Fig. 3). The conditional effects showed that the greatest contribution to the sum of the eigenvalues was due to soil P (0.26), followed by Date (0.08), soil N (0.05), GP (0.04) and soil S (0.03). The significance of these explanatory variables were: soil P ($P < 0.01$), Date ($P < 0.01$), GP ($P < 0.01$), soil N ($P < 0.05$) and soil S (<0.05).

The RDA analysis found that 70% of the variation was explained by axis-1 and 18% by axis-2 of the triplot. The acute angles between the lines show that LegumeDM was strongly positively correlated with soil P as well as with soil N, soil S and SR but had little correlation with GP or DeadDDM. These latter two factors were strongly negatively correlated with each other. GreenDDM was also positively correlated with soil N and somewhat positively correlated with soil P and legume DM. Soil P, S and N were also positively correlated with each other.

Over the dates examined in this analysis, the average SR on farmlets A, B and C were 11.7, 7.2 and 7.6 dse/ha, the average proportion of each farmlet grazed on any 1 day was 0.55, 0.56

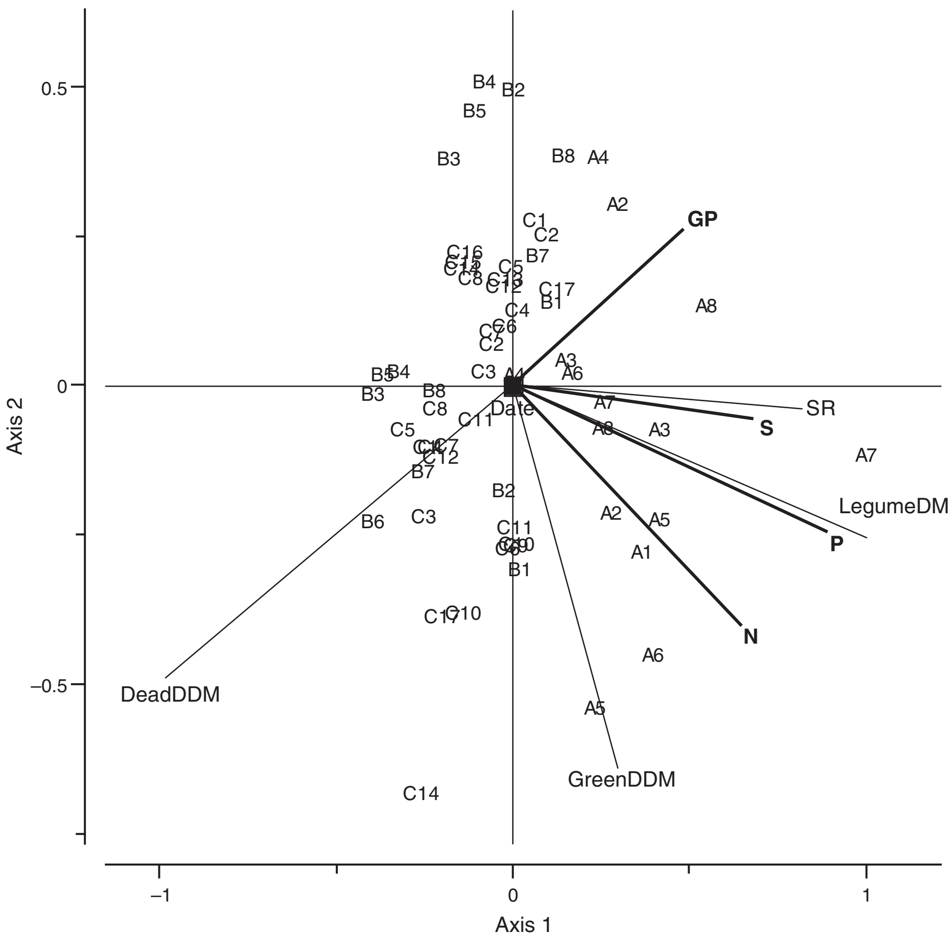

Fig. 3. Triplot from redundancy analysis showing relationships between pasture and grazing response variables green digestible herbage (GreenDDM), legume herbage (LegumeDM), dead digestible herbage (DeadDDM) and stocking rate (SR) and explanatory variables [Date, soil N, P and S and grazed proportion (GP)] over two soil sampling periods (March 2003–February 2005 and February 2005–March 2006). The paddocks of each farmlet (A, B and C) are designated by letter-number combinations. Lines subtended by small angles tend to be positively correlated while those subtended by oblique angles tend to be negatively correlated. Lines at right-angles are uncorrelated with each other.

and 0.17 while the average weight of legume herbage per farmlet was 29.1, 6.5 and 5.7 kg DM/ha, respectively.

The letter-number codes in Fig. 3 show alignment of farmlet A paddocks with the right side of axis-1 and thereby a positive association with higher levels of N, P and S as well as with increased GreenDDM, LegumeDM and SR; in contrast, paddocks of both farmlets B and C are mostly aligned to the left of centre. Thus, it is clear that soil nutrient levels had a significant effect on important pasture variables such as increasing the amount of legume present and the amount of GreenDDM as well as the SR able to be supported by those pastures.

Discussion and conclusions

It is noteworthy that, despite the substantial evidence of the value of enhanced soil fertility to livestock production in the region, producer members of the Cicerone Project wanted this issue revisited in the Cicerone farmlet experiment. In the view of those members, the value of investments in fertiliser and pasture renovation were still in question. The assessment of soil fertility across all paddocks of each farmlet in this whole-farmlet trial proved to be a challenging task as fertiliser applications varied with pasture renovation strategies and soil tests for each farmlet and paddock, creating non-uniform experimental conditions which, although uncommon in published fertiliser experiments, are common on real farms. Cicerone members wanted soil fertility differences explored at the whole-farmlet scale, rather than in small scale research trials, in order to better represent realistic farming scenarios. The farmlet trial was therefore able to capture the full expression of increased soil fertility through its effects on pasture species, herbage mass, nutritive value and SR.

Although the trial produced several significant findings in relation to soil fertility, the capacity of this farmlet experiment to satisfactorily answer the concerns of livestock producers was limited by several factors. First, as noted by Jones *et al.* (1995), the effects of changes in soil fertility and its interactions with botanical composition and SR are commonly observed to change over many years; in the present experiment, pasture renovation continued from 2000 up until 2004 while soil fertility differences were imposed especially over the first 3 years of the trial, resulting in farmlet parameters not reaching plateau conditions (Saul 2005) during the trial. Second, as demonstrated by Behrendt *et al*. (2013*b*), the soil moisture conditions experienced throughout the trial were below long-term median levels, thus limiting the expression of soil fertility changes as they affect pasture growth. Third, due to project resource constraints, fertilisers were not able to be applied in the last 2 years of the trial, which limited the ability to consistently maintain the target soil fertility levels on each of the farmlet treatments.

In spite of these constraints, the differences that were achieved between farmlets in soil P and S levels were consistent with the findings of much other research in terms of soil test (Burkitt *et al*. 2002) and effects on SR (Cayley *et al*. 1999). The soil fertility levels on farmlets B and C were maintained close to their target values of P and S by applying similar rates of fertiliser, suggesting that the intensive rotational grazing practised on farmlet C did not lead to substantial increases in levels of soil nutrients, such as P, as suggested by some (McCosker 2000; Cawood 2004).

As no measurements of the spatial distribution of nutrients within paddocks were taken, it cannot be concluded that any of the farmlet systems had different effects on the development of zones of nutrient depletion or concentration. However, as noted in a related paper by Shakhane *et al*. (2013*b*), there was evidence that 'patch' grazing developed on the typical farmlet B compared with the other farmlets and thus this farmlet may have resulted in a more uneven distribution of nutrients through spatial concentrations of dung and urine in sheep 'camps' over time. As noted by Simpson *et al*. (2011), the uneven distribution of animal excreta can be an important factor constraining efforts to improve the efficiency of P use, especially in grazed systems.

The multivariate analysis showed that plant-available P and S were positively associated with increased levels of LegumeDM and GreenDDM but had little relationship with the differences in grazing management represented by GP (Fig. 3). The significant effects of soil P and, at times, soil N and S, within this farmlet experiment have been reported in related papers within this Special Issue on botanical composition (Shakhane *et al*. 2013*b*), potential pasture growth rate (Donald *et al*. 2013), pasture quality (Shakhane *et al*. 2013*a*), animal liveweights and SR (Hinch *et al*. 2013*a*), sheep reproduction (Hinch *et al*. 2013*b*) and wool production and value (Cottle *et al*. 2013). The economic aspects of the different soil fertility strategies have also been explored in relation to profitability (Scott *et al*. 2013*a*) and optimisation (Behrendt *et al*. 2013*a*). An integrated overview of the most significant relationships between the various components of the three whole-farm systems investigated has been described by Scott *et al*. (2013*b*). It has commonly been observed in pasture fertility trials on the Northern Tablelands, and elsewhere in southern Australia, that fertiliser P initially stimulates clover growth, which in turn fixes N that stimulates the growth of associated grasses (Robinson and Lazenby 1976). The grasses that grow under this increased fertility regime are of higher nutritive value and can support higher SR and higher animal growth rates (Saul *et al*. 1999). The response to increased fertility was therefore through a combination of improvements in species composition (Shakhane *et al*. 2013*b*), potential pasture growth (Donald *et al*. 2013) and nutritive value (Shakhane *et al*. 2013*a*).

In the Cicerone farmlet trial, tall fescue (*Festuca arundinacea*) was used as the responsive grass species however there is strong producer interest in the use of native grass species on the Northern Tablelands. Whalley *et al*. (1976) found that the addition of fertiliser P to a naturalised pasture dominated by *Austrodanthonia* spp. increased both the proportion of white clover and annual pasture production. Their data confirms that the succession of legumes driven by improved fertility, subsequently resulting in increased grass growth, also applies to native pastures.

The reduction of fertiliser inputs on the higher-fertility treatment led to soil test values that were below the targets, but still substantially greater than the other treatments (Fig. 2). There was therefore a buffer of fertility that would favour the improved species over low-fertility invaders. Improved resilience and performance of pastures where soil P fertility is maintained at higher levels with regular inputs of fertiliser have been previously observed in Northern NSW (Mears *et al*. 1993). A lower-fertility pasture is more prone to invasion by less desirable species (Cook *et al*. 1978) and grazing management plays a larger role in maintaining a desirable botanical composition (Cook *et al*. 1978). A higher-fertility system is therefore better buffered from short-term periods of high fertiliser prices or low commodity prices. The substantial differences between farmlet A and the other two farmlets confirm the findings of Waller *et al*. (2001) who showed that 'soil fertility and pasture improvement have a much greater impact on animal productivity than changes to grazing method'.

Concern is sometimes expressed within the community at the environmental risk associated with increasing SSP inputs, with reference to SSP application to pasture as the driver behind eutrophication in inland river systems. However, FNLI modelling suggested that the risk of P loss from any of the farmlet systems was low. Furthermore, the average application rate of 13.1 kg P/ha.year was only just greater than a maintenance P application rate for farmlet A, so soil P levels were unlikely to rise further. As reported by Cayley *et al*. (2002), even high rates of fertiliser P have not led to environmental problems. Issues of nitrate leaching and soil acidification are known to be lower in summer-dominant rainfall regions, such as the Northern Tablelands of NSW, than in southern Australia with winter-wet, summer-dry conditions (McCaskill *et al*. 2003).

It is clear that soil fertility, and especially levels of available P, S and N, have profound flow-on effects not only on pastures but also on livestock and their products and thereby on whole-farm productivity and economics. At the current time, fertiliser prices are considered to be high and yet, in spite of this, investments in fertiliser can still be profitable over the long term (Behrendt *et al*. 2013*a*). It is concluded that, consistent with the approach taken in this farmlet trial, especially when fertiliser prices are high, that livestock producers are well advised to carry out regular soil testing of all farm paddocks and to fertilise each paddock, with the most appropriate fertiliser, according to test results to ensure that any investments in soil fertility are most likely to be effective and economic.

As shown by much of the earlier literature discussed above, this recommendation is not new. Maintaining soil fertility has been described in the past by livestock producers as essential (Nixon 1999) as well as profitable, even through droughts, by both researchers (Walker and Kearins 1986) and farmer groups (Trompf *et al*. 1998). This whole-farmlet experiment has confirmed, once again, the fundamental importance of maintaining adequate soil fertility through soil testing and fertiliser applications in order to optimise long-term profits without significant environmental risk.

Acknowledgements

The Cicerone farmlet trial was supported financially by taxpayers and wool producers via Australian Wool Innovation as well as by the Australian Sheep CRC and the University of New England. Valuable in-kind contributions were made from CSIRO, NSW Department of Primary Industries and the University of New England. The assistance provided in data analysis by Mr Duncan Mackay is gratefully acknowledged.

References

Barrow N, Carter E (1978) A modified model for evaluating residual phosphate in soil. *Australian Journal of Agricultural Research* **29**, 1011–1021. doi:10.1071/AR9781011

Behrendt K, Scott JM, Cacho O, Jones R (2013*a*) Simulating the impact of fertiliser strategies and prices on the economics of developing and managing the Cicerone Project farmlets under climatic uncertainty. *Animal Production Science* **53**, 806–816. doi:10.1071/AN11173

Behrendt K, Scott JM, Mackay DF, Murison R (2013*b*) Comparing the climate experienced during the Cicerone farmlet experiment against the climatic record. *Animal Production Science* **53**, 658–669. doi:10.1071/AN12300

Blair G, Chinoim N, Lefroy R, Anderson G, Crocker G (1991) A soil sulfur test for pastures and crops. *Australian Journal of Soil Research* **29**, 619–626. doi:10.1071/SR9910619

Burkitt LL, Gourley CJP, Sale PWG (2002) Changes in bicarbonate-extractable phosphorus over time when P fertiliser was withheld or reapplied to pasture soils. *Australian Journal of Soil Research* **40**, 1213–1229. doi:10.1071/SR02012

Cawood M (2004) Working with Nature on Lana In 'The Land'. July 26, 2004.

Cayley JWD, Kearney GA, Saul GR, Lescun CL (1999) The long-term influence of superphosphate and stocking rate on the production of spring-lambing Merino sheep in the high rainfall zone of southern Australia. *Australian Journal of Agricultural Research* **50**, 1179–1190. doi:10.1071/AR98198

Cayley JWD, Saul GR, McCaskill MR (2002) High-fertility pastures in south-west Victoria can be economically and environmentally sustainable. *Wool Technology and Sheep Breeding* **50**, 724–729.

Clark DA (2010) Contribution of farmlet scale research in New Zealand and Australia to improved dairy farming systems. In 'Proceedings of the 4th Australasian dairy science symposium'. Lincoln University, Christchurch, New Zealand. (Eds GR Edwards, RH Bryant) pp. 112–124. (Caxton Press: Christchurch) Available at http://www.sciquest.org.nz/node/69343 [Verified 26 March 2013]

Colwell JD (1963) The estimation of the phosphorus fertiliser requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 190–197. doi:10.1071/EA9630190

Cook SJ, Blair GJ, Lazenby A (1978) Pasture degeneration. II. The importance of superphosphate, nitrogen and grazing management. *Australian Journal of Agricultural Research* **29**, 19–29. doi:10.1071/AR9780019

Cottle D, Gaden CA, Hoad J, Lance D, Smith J, Scott JM (2013) The effects of pasture inputs and intensive rotational grazing on superfine wool production, quality and income. *Animal Production Science* **53**, 750–764. doi:10.1071/AN12289

CSIRO (1964) 'Soil and pasture research on the Northern Tablelands, New South Wales.' (CSIRO Publishing: Melbourne) 81 pp.

Donald GE, Scott JM, Vickery PJ (2013) Satellite derived evidence of whole farmlet and paddock responses to management and climate. *Animal Production Science* **53**, 699–710. doi:10.1071/AN11179

Edwards C, Duncan M (2002) Extension activities improve producer awareness of soil health. In 'Proceedings of the 17th annual conference of the Grassland Society of NSW 2002'. (Ed. A Bowman) pp. 48–49. (Grassland Society of NSW Inc.: Orange)

Goh KM, Nguyen ML (1992) Fertiliser needs for sustainable agriculture in New Zealand. In 'Proceedings of the international conference on sustainable land management, Napier, Hawkes Bay, New Zealand'. (Ed. PR Henriques) pp. 119–133.

Hinch GN, Hoad J, Lollback M, Hatcher S, Marchant R, Colvin A, Scott JM, Mackay D (2013*a*) Livestock weights in response to three whole-farmlet management systems. *Animal Production Science* **53**, 727–739. doi:10.1071/AN12201

Hinch GN, Lollback M, Hatcher S, Hoad J, Marchant R, Mackay DF, Scott JM (2013*b*) Effects of three whole-farmlet management systems on Merino ewe fat scores and reproduction. *Animal Production Science* **53**, 740–749. doi:10.1071/AN12440

Holford I, Crocker G (1988) Efficacy of various soil phosphate tests for predicting phosphate responsiveness and requirements of clover pastures on acidic tableland soils. *Australian Journal of Soil Research* **26**, 479–488. doi:10.1071/SR9880479

Isbell RF (1996) 'The Australian soil classification.' (CSIRO Publishing: Melbourne)

Jones RM, Jones RJ, McDonald CK (1995) Some advantages of long-term grazing trials, with particular reference to changes in botanical composition. *Australian Journal of Experimental Agriculture* **35**, 1029–1038. doi:10.1071/EA9951029

Kaine G, Doyle B, Sutherland H, Scott JM (2013) Surveying the management practices and research needs of graziers in the New England region of New South Wales. *Animal Production Science* **53**, 602–609. doi:10.1071/AN11170

McCaskill MR, Ridley AM, Okom A, White RE, Andrew MH, Michalk DL, Melland A, Johnston WH, Murphy SR (2003) SGS Nutrient Theme: environmental assessment of nutrient application to extensive pastures in the high rainfall zone of southern Australia. *Australian Journal of Experimental Agriculture* **43**, 927–944. doi:10.1071/EA03020

McCosker T (2000) Cell grazing – the first 10 years in Australia. *Tropical Grasslands* **34**, 207–218.

Mears PT, Havilah EJ, Price GH, Darnell RE, Mclennan DJ, Wilson C (1993) Superphosphate maintains soil fertility and beef production on grazed white clover pastures in the subtropics. 1. Residual soil phosphorus, sulfur, and nitrogen, and pasture growth responses. *Australian Journal of Experimental Agriculture* **33**, 425–434. doi:10.1071/EA9930425

Melland AR, Gourley CJP, Smith AP, Tarbotton IS, Peverill KI (2004) Developing a farm nutrient loss index for grazed pastures in Australia. In 'SuperSoil 2004: 3rd Australian New Zealand soils conference'. University of Sydney, Australia. (Ed. B Singh) (The Regional Institute Ltd) Available at http://www.regional.org.au/au/asssi/ [Verified 26 March 2013]

Morley FHW, Spedding CRW (1968) Agricultural systems and grazing experiments. *Herbage Abstracts* **38**, 279–287.

Murison R, Scott JM (2013) Statistical methodologies for drawing causal inference from an unreplicated farmlet experiment conducted by the Cicerone Project. *Animal Production Science* **53**, 643–648. doi:10.1071/AN11331

Nixon J (1999) Developing and maintaining productive pastures. In 'Proceedings of the 14th annual conference of the Grasslands Society of NSW, Queanbeyan, NSW'. (Eds D Garden, HL Davies, D Michalk, H Dove) pp. 91–94. (Grasslands Society of NSW Inc.: Orange)

R Development Core Team (2011) 'R: a language and environment for statistical computing.' (R Foundation for Statistical Computing: Vienna) Available at http://www.R-project.org [Verified 26 March 2013]

Robinson G, Lazenby A (1976) Effect of superphosphate, white clover and stocking rate on the productivity of natural pastures, Northern Tablelands, New South Wales. *Australian Journal of Experimental Agriculture* **16**, 209–217. doi:10.1071/EA9760209

Saul GR (2005) Summing up: Cicerone – a 'Mexican's' perspective. In 'The Cicerone farms: under the microscope'. Armidale, NSW. (Ed. JM Scott) pp. 83–88. (The Cicerone Project Inc. and Centre for Sustainable Farming Systems, University of New England: Armidale)

Saul GR, Kearney GA, Flinn PC, Lescun CL (1999) Effects of superphosphate fertiliser and stocking rate on the nutritive value of perennial ryegrass and subterranean clover herbage. *Australian Journal of Agricultural Research* **50**, 537–545. doi:10.1071/A98138

Schafer B (1980) A description of the soils on the CSIRO Pastoral Research Laboratory property, Chiswick, Armidale NSW. CSIRO Technical Bulletin No. 8.

Scott JF, Scott JM, Cacho OJ (2013*a*) Whole-farm returns show true profitability of three different livestock management systems. *Animal Production Science* **53**, 780–787. doi:10.1071/AN11248

Scott JM, Behrendt K, Colvin A, Scott F, Shakhane LM, Guppy C, Hoad J, Gaden CA, Edwards C, Hinch GN, Cacho OJ, Donald GE, Cottle D, Coventry T, Williams G, Mackay DF (2013*b*) Integrated overview of results from a farmlet experiment which compared the effects of pasture inputs and grazing management on profitability and sustainability *Animal Production Science* **53**, 841–855. doi:10.1071/AN12284

Scott JM, Gaden CA, Edwards C, Paull DR, Marchant R, Hoad J, Sutherland H, Coventry T, Dutton P (2013*c*) Selection of experimental treatments, methods used and evolution of management guidelines for comparing and measuring three grazed farmlet systems. *Animal Production Science* **53**, 628–642. doi:10.1071/AN12265

Scott JM, Munro M, Rollings N, Browne W, Vickery PJ, Macgregor C, Donald GE, Sutherland H (2013*d*) Planning for whole-farm systems research at a credible scale: subdividing land into farmlets with equivalent initial conditions. *Animal Production Science* **53**, 618–627. doi:10.1071/AN11176

Shakhane LM, Mulcahy C, Scott JM, Hinch GN, Donald GE, Mackay DF (2013*a*) Pasture herbage mass, quality and growth in response to three whole-farmlet management systems. *Animal Production Science* **53**, 685–698. doi:10.1071/AN12262

Shakhane LM, Scott JM, Murison R, Mulcahy C, Hinch GN, Morrow A, Mackay DF (2013*b*) Changes in botanical composition on three farmlets subjected to different pasture and grazing management strategies. *Animal Production Science* **53**, 670–684. doi:10.1071/AN11177

Simpson R, Oberson A, Culvenor R, Ryan M, Veneklaas E, Lambers H, Lynch J, Ryan P, Delhaize E, Smith F, Smith S, Harvey P, Richardson A (2011) Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. *Plant and Soil* **349**, 89–120.

Trompf JP, Sale PWG, Saul G, Shovelton J, Graetz B (1998) Changes in practices and decisions resulting from the paired-paddock model used in the Grassland's Productivity Program. *Australian Journal of Experimental Agriculture* **38**, 843–853. doi:10.1071/EA98058

Walker R, Kearins R (1986) Fertilizer and stocking rate strategies for sustained profitability. In 'Proceedings of the 1st annual conference of the Grasslands Society of NSW, Richmond, NSW'. (Ed. WJ McDonald) pp. 56–65. (Grassland Society of NSW Inc.: Orange)

Waller RA, Sale PWG, Saul GR, Kearney GA (2001) Tactical versus continuous stocking in perennial ryegrass-subterranean clover pastures grazed by sheep in south-western Victoria – 3. Herbage nutritive characteristics and animal production. *Australian Journal of Experimental Agriculture* **41**, 1121–1131. doi:10.1071/EA01019

Whalley R, Robinson G, Taylor J (1976) General effects of management and grazing by domestic livestock on the rangelands of the Northern Tablelands of New South Wales. *The Rangeland Journal* **1**, 174–190. doi:10.1071/RJ9780174

Zuur AF, Ieno EN, Smith GM (2007) 'Analysing ecological data.' (Springer: New York)