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The effects of pasture inputs and intensive rotational grazing on superfine wool production, quality and income

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Abstract. A farmlet experiment was conducted between July 2000 and December 2006 as part of the Cicerone Project, which sought to enhance the profitability and sustainability of grazing enterprises on the Northern Tablelands of New South Wales, Australia. A self-replacing Merino enterprise was grazed as the dominant livestock enterprise, together with ~20% of the carrying capacity as cattle, on each of three farmlet treatments: higher levels of soil fertility and pasture renovation with flexible rotational grazing over eight paddocks (farmlet A), moderate soil fertility and pasture renovation with flexible rotational grazing over eight paddocks (farmlet B) and moderate soil fertility and pasture renovation with intensive rotational grazing over 37 paddocks (farmlet C). Prior to commencement of the trial, the three 53-ha farmlets were allocated equivalent areas of land based on soil type, slope and recent fertiliser history.

This paper describes the effects of the three pasture and grazing management strategies on the production, quality and value of the wool produced per head, per ha and per farmlet. Up until 2001 there were no differences in wool production between farmlets. Thereafter, significant differences between farmlets emerged in greasy fleece weight per head and price received per kg of fleece wool. For example, the clean fleece value averaged over the 2003–05 shearings for all hoggets, ewes and wethers was 1531, 1584 and 1713 cents/kg for farmlets A, B and C, respectively.

There were small but significant differences, which varied between sheep class and year, between the farmlets in average fibre diameter and staple length but less so with staple strength. In general, while the differences between farmlets in staple strength varied over time, farmlets A and B tended to have wool with longer staple length and broader fibre diameter than farmlet C and this affected wool value per kg.

Differences in wool income per ha between farmlets grew in later years as the farmlet treatments took effect. In spite of farmlet A having a slightly lower wool value per kg, after taking into account its greater fleece weight per head and its higher stocking rate, the total wool income per ha was higher than on either farmlets B or C. The average gross wool income per ha from 2003 to 2005 was $303, $215 and $180 for farmlets A, B and C, respectively. The highest amount of greasy wool produced was in 2004 when 38.2, 26.5 and 21.5 kg/ha was harvested from farmlets A, B and C, respectively.

The fibre diameter profiles of 2-year-old ewes showed similar profiles for farmlets A and B but a significantly finer fibre diameter profile for farmlet C ewes due to intensive rotational grazing. However, sheep on all three farmlets produced wool with high staple strength.

Multivariate analyses revealed that greasy fleece weight, staple length and staple strength were significantly positively correlated with the proportion of the farm grazed at any one time, and with soil phosphorus, legume herbage and green digestible herbage thus highlighting the significant influence of pasture and soil inputs and of grazing management on wool production and quality.

Additional keywords: cell grazing, farming systems, fibre diameter profiles.

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Introduction

The production of superfine and fine wool continues to be a major agricultural enterprise on the Northern Tablelands of New South Wales (NSW), Australia, with grazing properties in the region typically running both sheep and cattle on farms with an average size of ~920 ha (Alford *et al*. 2003). The Northern Tablelands are situated in the northern portion of the high rainfall, temperate zone of Australia with summer-dominant rainfall and cold, frosty winters.

The quantity, type and quality of wool that can be produced in a region depend on a combination of sheep class, sheep genetics, environmental conditions and the pastures adapted to that region

(Masters *et al*. 2002). Understanding pasture and grazing management for profitable and sustainable livestock production has received increased attention recently with research and extension programs such as Prograze (Bell and Allan 2000), Sustainable Grazing Systems (Mason *et al*. 2003), the Lifetime Wool Project (Thompson *et al*. 2011), EverGraze (Badgery *et al*. 2012) and the Landscan training project (Anon. 2011*a*). The Cicerone Project arose in 1998 as a producer-led initiative to enhance the connection between graziers, researchers, extension specialists and consultants (Sutherland *et al*. 2013), and thereby to explore issues identified by the producer members of the Project.

Both wool production and wool quality are affected by pasture and grazing management (Pratley and Virgona 2010). Wool quality attributes with the highest effect on price include fibre diameter (FD), staple length (SL) and staple strength (SS) (Cottle 2010) but the premiums paid for these attributes change from year to year. Using an hedonic log price analysis, Ryan (2006) found the percentage price effects (elasticity) of a 1% change in FD, SL and SS were 2.5, 0.48 and 0.30%, respectively. An analysis of sources of clean price variation of all wool lots less than 18.5 micron sold in Australia in 2010–11 found that FD accounted for 69% of the model's price variance, while SL and SS each accounted for less than 3% (Cottle and Fleming, unpubl. data).

Some of the options available to superfine producers to influence wool production, quality and income are pasture management, grazing management, sheep genetics and the producer's calendar of operations. In terms of soil fertility and pasture management, Guppy *et al*. (2013) and Shakhane *et al*. (2013*b*) have shown the importance of phosphorus (P) and sulfur (S) fertility and pasture renovation in enhancing the botanical composition on the Cicerone farmlets. In Victoria, Warn *et al*. (2002) showed higher stocking rates can be sustained with fertiliser input and effective grazing management, while Cayley *et al*. (2002) found that increased fertiliser rates allowed an increase in pasture yield and quality, which led to an increase in stocking rate and subsequently to increased gross margins of $90–270/ha.

Set stocking and rotational grazing have been the most commonly examined treatments in experiments comparing different forms of grazing management. Graham *et al*. (2003) concluded that rotational grazing resulted in lower per head performance. Many researchers agree that rigid and inflexible grazing methods can restrict both animal and plant production (Norton 1998; Warn *et al*. 2002; Chapman *et al*. 2003; Graham *et al*. 2003) but the size of the effect depends on seasonal conditions. Warn *et al*. (2002) compared several grazing management treatments and concluded that optimum management depended on flexible, not fixed grazing intervals, based on the rate of plant growth; they also found no significant effect of grazing system or fertiliser level on wool cut per head or wool quality.

'Cell' grazing is a particular form of intensive rotational grazing, which commonly involves 30 or more paddocks, allowing short graze periods of several days with high stock densities followed by long rest periods (McCosker 2000). Cell grazing proponents have claimed that this system of grazing leads to increased pasture utilisation, greater species diversity, enhanced soil P, improved animal performance and higher profitability (McCosker 2000), although there is much conjecture about these claims in the literature (Norton 1998; Saul and Chapman 2002; Briske *et al*. 2011).

Stocking rate is one of the most important management decisions for both grazing and pasture management as it influences a wide range of production characteristics such as persistence of pasture, diet selection by animals, animal production rates, soil compaction, and wool quality and quantity (Morley 1981).

A survey of livestock producers on the Northern Tablelands of NSW, found that managing the nutritional requirements of ewes through both pregnancy and lactation was one of their biggest challenges (Kaine *et al*. 2013). While reproduction can cause reductions in SS, the effect can be minimised through effective pasture management, time of lambing and time of shearing (Robertson *et al*. 2000).

The use of fibre diameter profiles (FDP) measured using the OFDA2000 (Optical Fibre Diameter Analysis) or Laserscan (Brims *et al*. 1999) has been used by researchers (Brown and Schlink 2002; Brown *et al*. 2002) to explore how controlling FDP might improve wool processing performance (Hansford 1997; Thompson and Hynd 1998; Brown *et al*. 2000*b*; Adams and Cronje 2003). According to Hansford (1997), FD variation is the factor which most influences SS. A combination of minimum FD and rate of change along the staple has the greatest influence on the SS and position of break. This point of break along the wool fibre is commonly associated with a 'break' in the season which can cause a sharp change in animal nutrition (Thompson and Hynd 1998). There have been few studies of which statistical model can best determine when two profiles are statistically different or how to generate a single FD curve to represent several sheep in a treatment group (Hansford 2004).

The work reported in this paper explores the wool production, wool quality and wool income from the three Cicerone farmlets. The three different grazing and pasture management systems were compared for greasy fleece weight (GFW), FD, FDP, SL, SS, fleece price per kilogram, fleece value and gross wool production and income per ha.

The two hypotheses tested were that, compared with the typical management system of farmlet B:

(1) Higher rates of pasture renovation and of soil fertility (farmlet A) will result in higher per head and per ha wool production, and
(2) Intensive rotational grazing (farmlet C) will result in higher per head and per ha production of wool, while improving wool quality through SS and/or lower FD (resulting in greater wool income per ha).

Methods

Environment

The farmlet experiment was conducted on the CSIRO McMaster Research Station 'Chiswick', ~17 km south of Armidale, on the Northern Tablelands of NSW. The soils across all three farmlets were predominantly podsolic with some minor basalt areas (Scott *et al*. 2013*c*). The region is subject to a summer-dominant rainfall with a long-term average of ~780 mm. However, the rainfall received during the experimental period was generally below average, resulting in below-median soil moisture conditions which constrained pasture growth over much of the experimental period (Behrendt *et al*. 2013; Shakhane *et al*. 2013*a*).

Treatments

The farmlet experiment was set up at a scale which aimed to realistically represent different alternative management strategies on the Northern Tablelands of NSW. Due to the substantial size of the three farmlets (each 53 ha), replication of the design was prohibitive in cost and so it was essential that the three farmlets started out with equivalent levels of potential productivity. Through an iterative planning process, the land was allocated to each of the farmlets so that, at the commencement of the trial, each comprised equivalent areas of soil type, slope and recent fertiliser history (Scott *et al*. 2013*c*).

Following a survey of livestock producers commissioned by the Cicerone Project (Kaine *et al*. 2013) and considerable subsequent negotiation, the three treatments were decided upon (Scott *et al*. 2013*b*). Farmlet B was designed as the control treatment to represent 'typical' management on the Northern Tablelands. It received moderate levels of input of pasture renovation and soil fertility while flexible grazing management according to Prograze principles (Bell and Allan 2000), with its target herbage mass, herbage quality and animal condition benchmarks, was implemented across its eight paddocks. Farmlet A had the same grazing management and number of paddocks as farmlet B but had higher inputs of pasture renovation and soil fertility. Farmlet C had the same moderate inputs as farmlet B but employed intensive rotational grazing with short graze and long rest periods on 37 paddocks.

At the commencement of the trial, the target stocking rates set for the farmlets were 7.5 dry sheep equivalents (DSE)/ha for farmlet B (considered by Cicerone members to be a typical stocking rate for the area) and 15 DSE/ha for both farmlets A and C. In spite of these targets being set at the beginning of the trial, it was agreed that stocking rate would be an emergent property of each farmlet in common with the approach of other researchers (Chapman *et al*. 2003). It is important to point out that the grazing management treatments examined here represented two different forms of rotational grazing: one flexible (farmlets A and B) and the other intensive (farmlet C). 'Set stocking' or 'continuous grazing' was not included as a treatment as the members of the Cicerone Project felt it is rarely practised by graziers in the region (Scott *et al*. 2013*b*).

Livestock and pasture management decisions

In applying Prograze principles to farmlets A and B, management aimed to ensure that animals did not graze pastures below 500 kg DM/ha of green herbage mass while maintaining ewe fat scores above 2.5 (Scott *et al*. 2013*b*). Regular monthly assessments of pastures (Shakhane *et al*. 2013*a*) and regular weighing (Hinch *et al*. 2013*a*) and fat scoring (Hinch *et al*. 2013*b*) of livestock were essential components of applying these principles.

Over all years, the average length of grazing periods, at the level of paddocks and sub-paddocks, on farmlets A, B and C was 45, 75 and 11 days, respectively, while the length of rest periods was 64, 66 and 98 days, respectively (Walkden-Brown *et al*. 2013). As explained in detail in a related paper by Scott *et al*. (2013*b*), stocking rates were adjusted after management took into account assessments of pastures and stock condition and thereby determined the numbers of ewes to be joined on each farmlet in April–May of each year. Details of all stock moves and changes in stocking rate, stocking density and graze and rest periods have been provided in a related paper by Hinch *et al*. (2013*a*).

The dominant livestock enterprise was a self-replacing Merino flock, which comprised ~80% of the stocking rate (Scott *et al*. 2013*b*), in terms of DSE, on each farmlet with the balance stocked with cattle which were purchased and sold when opportunities arose due to surplus feed over the spring–summer period. Bias due to genetic differences was avoided by ensuring that animals were randomly allocated to farmlets as well as allowing the ewes from all three farmlets to run together with the same rams on peripheral paddocks outside the farmlets for 6 weeks during joining. As with stocking rate, differences in livestock performance such as reproduction and animal mortality (Hinch *et al*. 2013*b*) were treated as emergent properties of each farmlet system. Details of all pasture renovation and fertiliser applications on all paddocks, as well as of supplementary feeding, have been provided by Scott *et al*. (2013*b*).

Measurements

As the first shearing (August 2000) took place in the second month of the trial period, no wool data were recorded for that shearing as sufficient human resources were not available at that time. From the 2001 shearing onwards, individual fleeces were weighed and tested for FD with additional wool quality measurements being gathered using both OFDA2000 and Australian Wool Testing Authority (AWTA) measurements in subsequent years up to and including 2005. However, in the final year of the trial (2006), once again limited resources meant that no measurements could be taken of individual fleeces or quality.

Annual fleece measurements were made on hoggets, ewes and wethers. Fibre diameter and variation was measured using OFDA2000 (Peterson and Gherardi 2001) on hip-bone wool samples taken 2–3 weeks before shearing. On the same day, mid-side samples were taken for yield, SL, SS and point of break (percentages of tip, mid, and base breaks) but not vegetable matter (VM), and measured by AWTA (Sydney laboratory).

In addition, the effect of farmlet management system on the FDP and its relationship with SS was evaluated. The Cicerone farmlet experiment provided one of the flocks tested in a survey of fine wool flocks in the Northern Tablelands region (Smith *et al*. 2006). Fifteen ewes from each farmlet, born in spring 2002, were mid-side dye banded periodically in the 2003–04 wool-growing year and subsequently measured for FDP and SS in 2004. The measurements of FDP were carried out on two separate staples from the mid-side dye band sample using plastic slides with 5-mm increments.

The dye bands were applied on 12 December 2003, 137 days after shearing and again on 22 March 2004, after a further 101 days. The dye bands were removed after an additional

95 days, on 25 June 2004. Staple length was measured manually on 10 staples from each dye banded sample using a ruler. The distance was measured from the base of the staple to each dye band and from the base to the tip. The growth was then calculated for each period of measurement. Once the three lengths were determined, they were divided by the number of days in that measurement period to obtain an average growth rate for that period.

All livestock data, collected from July 2000 and wool data, collected from July 2001, and all other farmlet data, were stored and manipulated using a relational database maintained for all Cicerone Project experimental records (Scott *et al*. 2013*b*).

Wool income

The value of individual sheep fleeces was determined by valuing the fleece properties of each sheep that had clean fleece weight, FD, SL, SS and point-of-break measurements made in 2003–05 using a quadratic clean price model. This equation was derived from analysing the 17 704 Merino fleece lots that were sold in 2010–11 at Sydney or Newcastle sale centres that were less than 23.1-µm FD and less than or equal to 0.1% VM and had SL, SS and point-of-break measurements. This reflected the wool properties of the Cicerone sheep and their likely wool sale price.

$$\begin{aligned}
&Clean\ price\ (c\ per\ kg)\\
&\quad = 13\,715.3(\pm 255.7) - 1182.6(\pm 25.6)FD\\
&\quad + 26.3(\pm 0.68)FD^2 + 13.0(\pm 2.37)SL\\
&\quad - 0.08(\pm 0.01)SL^2 + 9.7(\pm 1.87)SS - 0.1(\pm 0.03)\mathrm{SS}^2\\
&\quad - 1.9(\pm 0.11)MB,\ r^2 = 0.58, RMSE = 306.03, P < 0.0001
\end{aligned}$$

where MB = mid-breaks (%).

The fleece value per kg was converted to per head and per ha values by multiplying by the relevant average clean fleece weight and numbers of stock in each class. Thus, for the purposes of comparing wool income between farmlets in this paper, the wool was valued as though it had all been stored and sold in 2011. The average fleece value was based on the skirted fleece weights so the wool income from skirtings and bellies were not taken into account in this analysis.

In addition, a value of wool was determined based on average values for different years and classes of sheep using the 'Woolcheque' valuation system (Anon. 2011*b*) maintained by the Australian Wool Exchange for Australian Wool Innovation. This assumed a 'spinners' style with near free (0.1%) vegetable matter evaluated using the SS data, which were only available for portions of sheep from each flock, so no discounts were assumed when SS was not measured. This provided a means of checking the veracity of the mean values achieved through the valuation of individual animal fleeces described above.

Statistical analyses

Being an unreplicated trial, statistical analyses could not use conventional methods of measuring treatment effects against experimental error. Issues relating to assigning causal inference to the farmlet treatments have been discussed in detail in a related paper by Murison and Scott (2013).

All data were examined for normality using quantile-quantile (QQ) plots (R Development Core Team 2011). In addition, pair plots (Zuur *et al*. 2007) were used to examine the degree of correlation measured by Pearson correlation coefficients using the software 'Brodgar' (version 2.7.2, Highland Statistics Ltd, Newburgh, UK), which provides an interface to the statistical software R (R Development Core Team 2011). The effects of farmlet treatments on GFW and the wool quality characteristics of FD, SL and SS were analysed as generalised linear models, using forwards and backwards selection, using a Gaussian distribution and identity link function (Zuur *et al*. 2007) with the significant factors determined after selecting the lowest Akaike information criterion values.

The fleece value data for individual sheep were also explored for normality using a QQ plot and subsequently analysed using a generalised additive model (Zuur *et al*. 2007) with sheep class, farmlet and year and two- and three-way effects between these three main effects.

Before analysis of FDP for treatments were conducted, a treatment group curve was calculated. Two FDPs for each hogget were used to develop an individual FDP curve. Any FDP for staples longer than 95 mm were ignored as the few records with long fibre lengths were not represented across all three farmlets and hence prevented the calculation of significant differences for those fibre segments. Out of 88 FDP records only four were thus excluded based on long fibre lengths (4.5% of the dataset).

All FDP data were tested for normality using a Shapiro–Wilk test of normality and QQ plots using R and were found to be normally distributed. Basis polynomial splines, or B-splines (R Development Core Team 2011), which permit particular points on a curve to be influenced by every other point on the curve, were used as they enable statistical comparison at points along the profile. The differences between segments of the curves were tested using a linear mixed effects model in R. The B-spline was fitted with the following model:

$$y = \sum_{v=1}^{v} s_v(x_v) + \varepsilon,\ \ \varepsilon \sim N(0, \sigma^2)$$

where $s_v(x_v)$ denotes a smooth function of the predictor variable, fibre segment length (x_v). An analysis of combined curves for each treatment was carried out by fitting bessel functions to each of the segments. The mean weights of each bessel function for each treatment were compared using Student's *t*-tests.

Results

Tests for normality of the wool data using QQ plots showed no need for data transformations. The results for GFW per head and the wool quality parameters of FD, SL and SS are presented over time with 95% confidence intervals for all hoggets, mature ewes and mature wethers in Fig. 1.

Fleece weight

The GFW for mature ewes (>2 years) was similar between farmlets in 2001 but thereafter, farmlet A and B ewes had significantly ($P < 0.05$) higher GFW by 0.3–0.5 kg/head than farmlet C (Fig. 1). Similarly, the GFW for hoggets was not different between the three farmlets in 2001 but, thereafter,

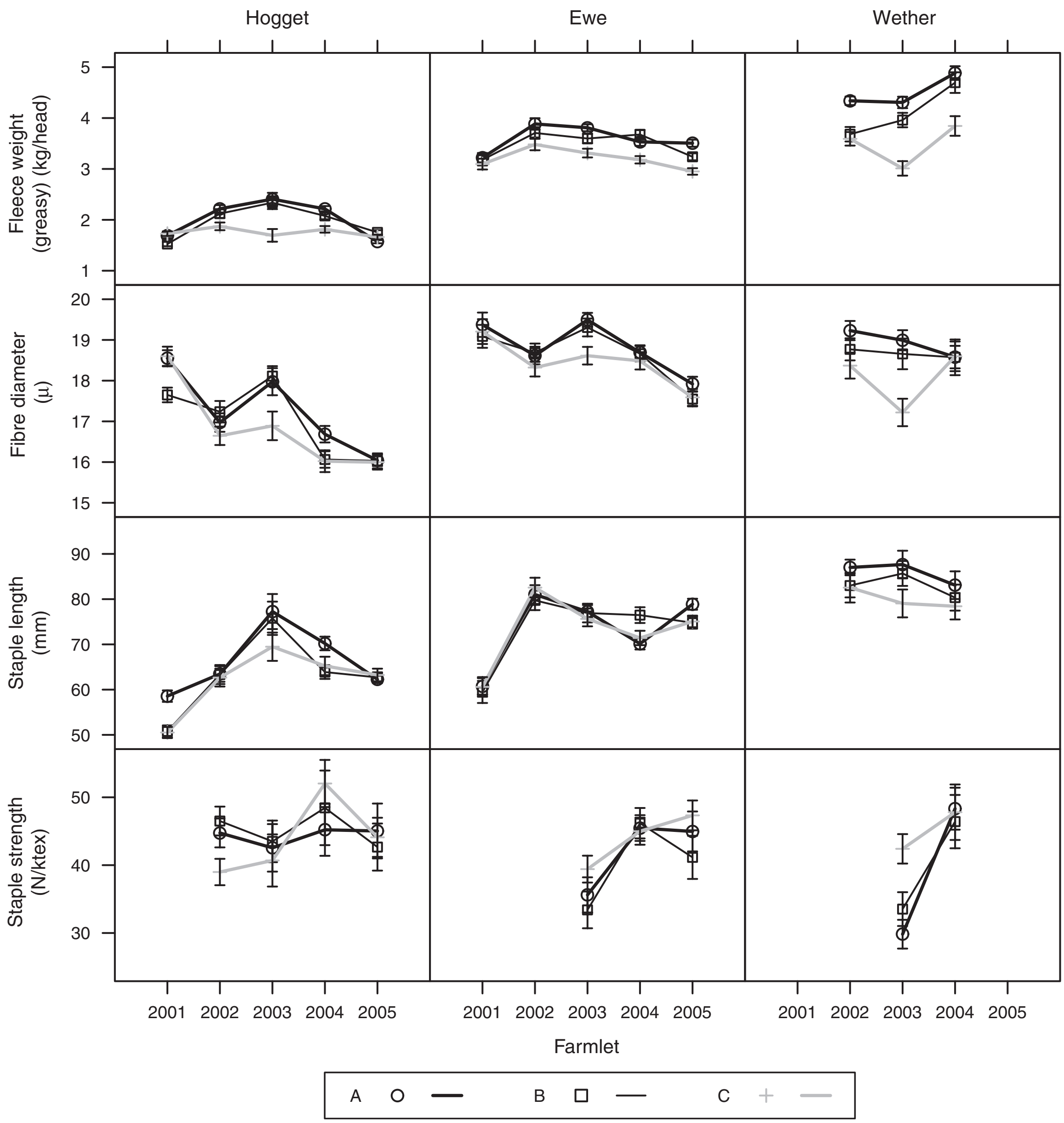

Fig. 1. Average greasy fleece weight (±95% confidence intervals), fibre diameter, staple length and staple strength for hoggets, mature ewes and mature wethers from farmlets A, B and C from 2001 to 2005.

farmlet A and B hoggets had significantly ($P < 0.05$) higher GFW (0.2–0.7 kg/head) than farmlet C (Fig. 1) except in 2005 when hoggets on all farmlets produced similar quantities of wool.

In 2002 and 2003, the GFW for mature wethers (>2 years) was significantly ($P < 0.05$) higher on farmlet A than on farmlet B, which in turn was significantly higher than on farmlet C in 2003 and 2004. In some years, the differences between farmlets in fleece weight of wethers were substantial (1.0–1.3 kg/head) (Fig. 1).

The relationship between GFW and explanatory factors was explored using a generalised linear model as a function of stocking rate, grazed proportion, green digestible herbage, legume herbage, level of supplement fed, sex, age and year. This showed the significant factors to be sex, grazed proportion, year, legume herbage, supplement and two-way interactions between year and supplement and year and grazed proportion.

As the farmlet experiment was to be terminated by the end of 2006, and as Project resources were limited at that time, no data were collected on individual fleeces at the 2006 shearing. In that year, ~25 bales were harvested with adult wool having an average of 17 micron whereas the hogget wool averaged 15 micron (J. Hoad, pers. comm.).

Wool quality characteristics

Ewes were selected for fineness each year and hence Fig. 1 shows a downward trend in FD of ~2 and 1 micron in hogget and ewe wool, respectively, over the 4 years from 2001 to 2005. As the wethers were from a similar cohort over the years measured, there was little change in the fineness of their wool over the same time period.

In general, the average FD of wool from hoggets, ewes and wethers was similar between farmlets A and B and lower in some years on farmlet C. A generalised linear model of FD found the most significant factors responsible for the differences, selected with the lowest Akaike information criterion values, to have been year, legume herbage, green digestible herbage, sex and two-way interactions between year and green digestible herbage and year and legume herbage.

The differences in SL and SS between sheep class, farmlets and years were less consistent than the differences in GFW and FD. In general, sheep on farmlet C tended to have lower SL but higher SS than sheep on either of the other two farmlets. In the case of SL, the significant factors found from a generalised linear model analysis were sex, year, grazed proportion, legume herbage and green digestible herbage whereas for SS, the most significant factors were found to be year, grazed proportion, age, supplement and a two-way interaction between year and grazed proportion. Thus, the factors associated with farmlet treatment, which significantly affected changes in wool production and quality characteristics were the amounts of green digestible herbage and legume (significantly higher on farmlet A) and the differences in grazed proportion (much lower on farmlet C).

Fibre diameter profiles

Figure 2 shows the FDP from the 15 measured sheep on each farmlet fitted with B-splines as well as a single combined curve to describe each farmlet treatment. The group profiles were also fitted with upper and lower curves to show the confidence interval of the fitted estimates.

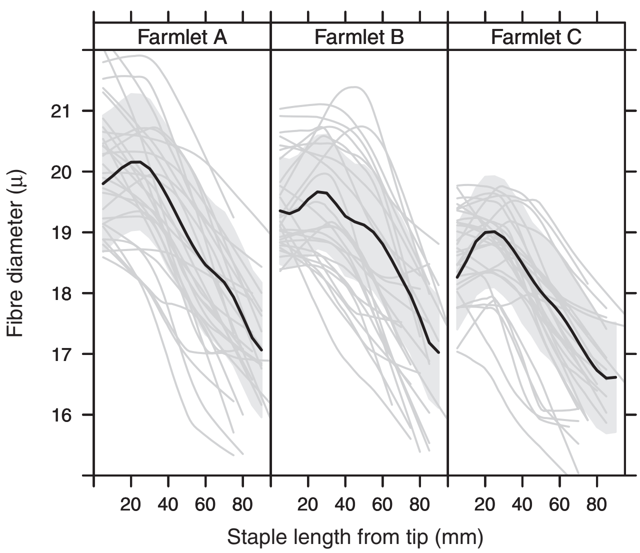

Fig. 2. Fibre diameter profiles showing relationship between fibre diameter and distance from tip of staple measured at shearing in 2004 from individual hogget sheep (02 drop) from farmlets A, B and C (grey lines = duplicate profiles for individual animals, black lines = fitted profiles, shaded area = ±95% confidence intervals of fitted lines).

The bessel functions fitted to each of the 13 segments indicated that there was a significant difference between at least two of the treatments ($P < 0.05$) at most of the bessel function points ($P < 0.001$) (Table 1). Whereas Table 1 shows no significant differences between farmlets A and B in FD for any segment, farmlet A differed significantly from farmlet C in the first 10 segments; farmlet B was significantly different to farmlet C in 7 of those 10 segments.

Table 2 shows the calculated growth rate of wool fibres of the ewes used for the FDP measurements. The daily wool growth rate was highest soon after shearing and lowest in the final measurement period which coincided with the point of minimum FD. The point of minimum FD normally occurs at the time of the year when the feed supply was most limiting. This was found to be at shearing time (early August) when pasture herbage mass was commonly at a minimum within the farmlet experiment (Shakhane *et al*. 2013*a*).

Wool production and value

The differences between farmlets for all shorn sheep and their quality characteristics and wool value calculations per kg, per head, per ha and per farmlet are presented in Table 3.

Although the wool price was mostly higher for farmlet C due to its slightly finer FD, this advantage was offset by its lower wool cut per head. The average wool price over the 2003–05 shearings for all hoggets, ewes and wethers, was 1531, 1584 and 1713 cents/kg for farmlets A, B and C, respectively (Table 3). When combined with the clean fleece weight, the average fleece values over the same period and sheep classes were $39.55, $40.12 and $36.60 for farmlets A, B and C, respectively. Analysis of the effects of farmlet, sheep class and year on clean fleece price was conducted with a generalised additive model using a Gaussian distribution with an identity link function which explained some 51.6% of the deviance. The following main effects and interactions were found to be significant ($P < 0.001$): farmlet, sheep class, year, farmlet by year, sheep

Table 1. Student's *t*-test comparison of bessel functions of fibre diameter profiles showing significant differences (shown in bold text, $P < 0.05$, *t*-test value >2.0) between farmlets over all fibre segments (5 mm) from tip to base

Fibre segment number	Farmlet comparisons AB	AC	BC
(Tip) 1	1.17	**4.03**	**2.04**
2	0.75	**2.16**	1.38
3	1.31	**2.01**	0.67
4	1.66	**3.15**	1.43
5	1.39	**4.08**	**2.56**
6	0.12	**3.32**	**3.19**
7	–0.77	**3.42**	**4.19**
8	–1.73	**2.52**	**4.03**
9	0.07	**3.37**	**3.16**
10	–0.22	**3.67**	**3.69**
11	0.52	1.51	0.89
12	0.62	0.73	0.09
(Base) 13	1.25	0.9	–0.3

Table 2. Average daily fibre growth rate and length for the three dye band periods for 15 ewes on each of farmlets A, B and C between shearings in 2003 and 2004

Farmlet	Period 1 (137 days) (28 July–12 December 2003)		Period 2 (101 days) (12 December 2003–22 March 2004)		Period 3 (95 days) (22 March–25 June 2004)	
	Fibre length (mm)	Daily fibre growth rate (mm/day)	Fibre length (mm)	Daily fibre growth rate (mm/day)	Fibre length (mm)	Daily fibre growth rate (mm/day)
A	40.2	0.29	24.4	0.28	20.4	0.22
B	37.7	0.28	31.0	0.31	22.0	0.23
C	34.8	0.25	26.7	0.26	20.7	0.22

class by year and farmlet by sheep class by year. The clean fleece price for the three-way interaction of farmlet, sheep class and year is shown in Fig. 3 with confidence intervals.

The most substantial difference in wool production between farmlets occurred because of changes that developed over time in stocking rates. Fig. 4*a* shows that, as the trial progressed, farmlet A supported a higher stocking rate than either of the other farmlets which were similar to each other. While farmlet B met its modest stocking rate target of 7.5 DSE/ha, farmlet A reached its target of 15 DSE/ha in only a few months (Hinch *et al*. 2013*a*). However, farmlet C was not able to support an increase in its stocking rate close to its target of 15 DSE/ha; nor did its stocking rate climb above that of farmlet B. Thus, the largest differences in wool value per ha and per farmlet were due to the changes in number of sheep shorn which diverged along with changes in stocking rate over time.

The maximum average quantity of greasy wool produced per ha was highest in 2004 being 32.4, 21.4 and 16.3 kg/ha for farmlets A, B and C, respectively. When this value was adjusted for the proportion of DSE each farmlet ran as sheep (versus cattle), which was deliberately maintained at similar proportions of sheep and cattle units on all three farmlets (Scott *et al*. 2013*b*), an estimate of total wool production can be made assuming that all grazing was by sheep. Thus, as ~80% of the stocking rate comprised sheep (Scott *et al*. 2013*b*), the differences in wool production per ha between farmlets, when adjusted to 100% of stocking rate being run as sheep, increased to the point when in 2004, farmlets A, B and C produced 38.2, 26.5 and 21.5 kg of greasy wool per ha, respectively (Fig. 4*b*).

Table 4 shows total wool income per ha and per farmlet, which were derived from the number of sheep shorn and the fleece value per head. Thus, the average wool value produced per ha over the three sheep classes for the period 2003–05 were $303, $215 and $180 for farmlets A, B and C, respectively. Similarly, the average annual wool income per farmlet over the same period was $16 085, $11 428 and $9449 for farmlets A, B and C, respectively (Table 4).

Relationships between wool parameters and explanatory factors

A pair plot of four main wool parameters [GFW, FD, SL and SS] with several explanatory variables revealed that the highest Pearson correlation coefficients for GFW were for age class (adult or hogget) (r = 0.77), sex (0.75), year (0.32), grazed proportion (0.32) and legume herbage (0.30). For FD and SL, the highest coefficients were for age (0.55 and 0.43, respectively), sex (0.45 and 0.45), year (0.45 and 0.40) and legume herbage (0.23 and 0.19). For SS, the highest coefficients were year (0.32) and sex (0.20).

A multivariate redundancy analysis (RDA) of some 958 wool records (Fig. 5) showed a significant (P < 0.01) relationship between the wool response variables GFW, FD, SL and SS and seven explanatory factors which, together, explained 43% of the variation in these characteristics. Fig. 5 shows that GFW was most strongly correlated with grazed proportion, supplement fed, legume herbage, green digestible herbage, age (maturity) and sex, whereas FD and SL were highly collinear and were positively correlated with GFW (P < 0.01). As stocking rate was only moderately significant as an explanatory factor (P = 0.07), it was excluded as a covariate; this suggests that the farmlet with the highest stocking rate (farmlet A) was able to sustain that rate without a significant effect on wool fleece weight per head or quality characteristics. SS tended to be negatively correlated with FD and SL.

A second RDA analysis was conducted to further explore the relationship between GFW, FD, SL and SS against a second set of explanatory factors of age, year, grazed proportion, sex, legume herbage and soil P. A pair plot of correlations showed that the highest correlations with GFW were: age (0.77), year (0.47), nitrogen (N) (0.54), S (0.50), P (0.43), legume herbage (0.36) and grazed proportion (0.33).

This analysis was based on a lesser dataset of 586 records (due to insufficient soil tests taken in 2002 and none in 2004); thus data were available only from 2 years (2003 and 2005). The factors of soil N, S and P were highly collinear and thus were restricted to the most significant factor, soil P. The significant explanatory variables were found to be sex, age, year, grazed proportion, legume herbage (P < 0.01) and soil P (P < 0.05). These factors explained 48% of the variation. The biplot from this analysis (Fig. 6) shows that FD and SL were most closely correlated with soil P, legume herbage and grazed proportion whereas GFW was most closely correlated with age, sex and grazed proportion. Thus, the production goal of producing more wool per sheep was best promoted by having a high proportion of the farm grazed at any one time (i.e. farmlets A and B) compared with farmlet C with its much lower grazed proportion. However, while SL was associated with higher soil P and legumes, so also was FD. Staple strength tended to be negatively correlated with legume herbage and soil P.

The trends in the significant covariates from the RDA analyses are shown in Fig. 7. These show that, over time,

Table 3. Details of numbers of sheep shorn and, where available, average greasy fleece weight, yield, clean fleece weight, fibre diameter, staple length, staple strength, point-of-break, modelled wool price and calculated clean fleece value per head and per ha for all hoggets, ewes and wethers on farmlets A, B and C from all shearings (2000–06)

Year	Hoggets			Ewes			Wethers			Average over classes		
	A	B	C	A	B	C	A	B	C	A	B	C
					Number shorn							
2000	–	–	–	374	351	373	–	–	–	–	–	–
2001	209	205	174	110	107	97	–	–	–	–	–	–
2002	99	89	80	103	117	93	144	57	55	–	–	–
2003	31	41	30	258	138	130	52	45	38	–	–	–
2004	128	73	64	337	210	191	50	45	37	–	–	–
2005	260	168	148	200	168	160	–	–	–	–	–	–
2006	134	93	94	224	140	147	119	–	–	–	–	–
Avg. (2003–05)	140	94	81	265	172	160	51	45	38	152	104	93
					Greasy fleece weight							
2001	1.7	1.5	1.7	3.2	3.2	3.1	–	–	–	–	–	–
2002	2.2	2.1	1.9	3.9	3.7	3.5	4.3	3.7	3.6	–	–	–
2003	2.4	2.3	1.7	3.8	3.6	3.3	4.3	4.0	3.0	–	–	–
2004	2.2	2.1	1.8	3.5	3.7	3.2	4.9	4.7	3.8	–	–	–
2005	1.6	1.8	1.7	3.5	3.2	3.0	–	–	–	–	–	–
Avg. (2003–05)	2.1	2.1	1.7	3.6	3.5	3.1	4.6	4.3	3.4	3.4	3.3	2.8
					Yield (%)							
2002	77.6	80.9	79.7	–	–	–	–	–	–	–	–	–
2003	80.0	79.3	77.4	77.9	79.7	80.5	80.5	81.5	78.7	–	–	–
2004	76.8	80.3	82.4	80.1	81.0	79.7	77.9	79.5	81.3	–	–	–
2005	79.7	79.7	81.7	78.8	80.5	79.4	–	–	–	–	–	–
Avg. (2003–05)	78.8	79.8	80.5	78.9	80.4	79.9	79.2	80.5	80.0	79.0	80.2	80.1
					Clean fleece weight (kg/head)							
2002	1.7	1.7	1.5	–	–	–	–	–	–	–	–	–
2003	1.9	1.9	1.3	3.0	2.9	2.7	3.5	3.2	2.4	–	–	–
2004	1.7	1.7	1.5	2.8	3.0	2.5	3.8	3.7	3.1	–	–	–
2005	1.3	1.4	1.4	2.8	2.6	2.3	–	–	–	–	–	–
Avg. (2003–05)	1.6	1.6	1.4	2.9	2.8	2.5	3.6	3.5	2.7	2.7	2.6	2.2
					Fibre diameter (μ)							
2001	18.5	17.6	18.6	19.4	19.1	19.2	–	–	–	–	–	–
2002	17.0	17.2	16.6	18.6	18.7	18.3	19.2	18.8	18.4	–	–	–
2003	18.0	18.1	16.9	19.5	19.3	18.6	19.0	18.7	17.2	–	–	–
2004	16.7	16.1	16.0	18.7	18.7	18.5	18.6	18.6	18.6	–	–	–
2005	16.0	16.0	16.0	17.9	17.5	17.6	–	–	–	–	–	–
Avg. (2003–05)	16.9	16.7	16.3	18.7	18.5	18.2	18.8	18.6	17.9	18.1	18.0	17.5
					Staple length (mm)							
2001	58.6	50.8	50.5	60.7	59.5	60.6	–	–	–	–	–	–
2002	72.0	65.8	64.0	81.0	79.7	82.6	87.0	83.0	82.6	–	–	–
2003	72.8	78.1	68.7	94.4	89.2	84.3	96.1	91.2	83.8	–	–	–
2004	73.6	73.2	71.0	88.6	92.4	81.6	98.0	95.0	88.6	–	–	–
2005	66.8	69.3	63.4	83.4	76.6	76.9	–	–	–	–	–	–
Avg. (2003–05)	71.1	73.6	67.7	88.8	86.1	80.9	97.1	93.1	86.2	85.7	84.2	78.3
					Staple strength (N/ktex)							
2002	44.7	46.5	39.0	–	–	–	–	–	–	–	–	–
2003	42.5	43.5	40.7	35.6	33.4	39.4	29.8	33.5	42.4	–	–	–
2004	45.2	48.4	52.0	45.5	46.2	45.0	48.3	46.4	47.8	–	–	–
2005	45.0	42.7	44.1	45.0	41.1	47.3	–	–	–	–	–	–
Avg. (2003–05)	44.3	44.9	45.6	42.0	40.2	43.9	39.1	40.0	45.1	41.8	41.7	44.9
					Point of break (% mid-breaks)							
2002	56.4	43.9	47.0	–	–	–	–	–	–	–	–	–
2003	24.1	27.4	17.0	65.4	50.4	27.8	90.4	95.7	26.8	–	–	–

Table 3. (*continued*)

Year	Hoggets A	Hoggets B	Hoggets C	Ewes A	Ewes B	Ewes C	Wethers A	Wethers B	Wethers C	Average over classes A	Average over classes B	Average over classes C
2004	78.7	64.5	83.4	29.4	27.9	45.8	12.5	20.8	27.5	–	–	–
2005	70.6	77.8	78.0	65.3	52.0	55.1	–	–	–	–	–	–
Avg. (2003–05)	57.8	56.6	59.4	53.4	43.4	42.9	51.4	58.2	27.2	54.2	52.7	43.2
Wool price (cents/kg clean)												
2002	1803	1737	1909	–	–	–	–	–	–	–	–	–
2003	1606	1571	1904	1220	1288	1466	1247	1316	1801	–	–	–
2004	1847	2066	2028	1436	1437	1451	1466	1464	1453	–	–	–
2005	2058	2057	2051	1541	1664	1636	–	–	–	–	–	–
Avg. (2003–05)	1837	1898	1994	1399	1463	1518	1357	1390	1627	1531	1584	1713
Fleece value (clean) ($/head)												
2002	31.04	29.79	28.50	–	–	–	–	–	–	–	–	–
2003	30.91	29.11	24.97	36.22	36.93	39.10	43.22	42.47	42.70	–	–	–
2004	31.41	34.46	30.29	40.61	42.82	36.75	55.77	54.62	45.39	–	–	–
2005	25.76	28.75	27.84	42.56	43.39	38.33	–	–	–	–	–	–
Avg. (2003–05)	29.36	30.77	27.70	39.80	41.05	38.06	49.50	48.54	44.05	39.55	40.12	36.60
Fleece value ($/ha)												
2002	58	50	43	–	–	–	–	–	–	–	–	–
2003	18	22	14	176	96	97	42	36	31	–	–	–
2004	76	47	37	258	169	134	53	46	32	–	–	–
2005	126	91	78	160	137	117	–	–	–	–	–	–
Avg. (2003–05)	73	54	43	198	134	116	47	41	31	106	76	63

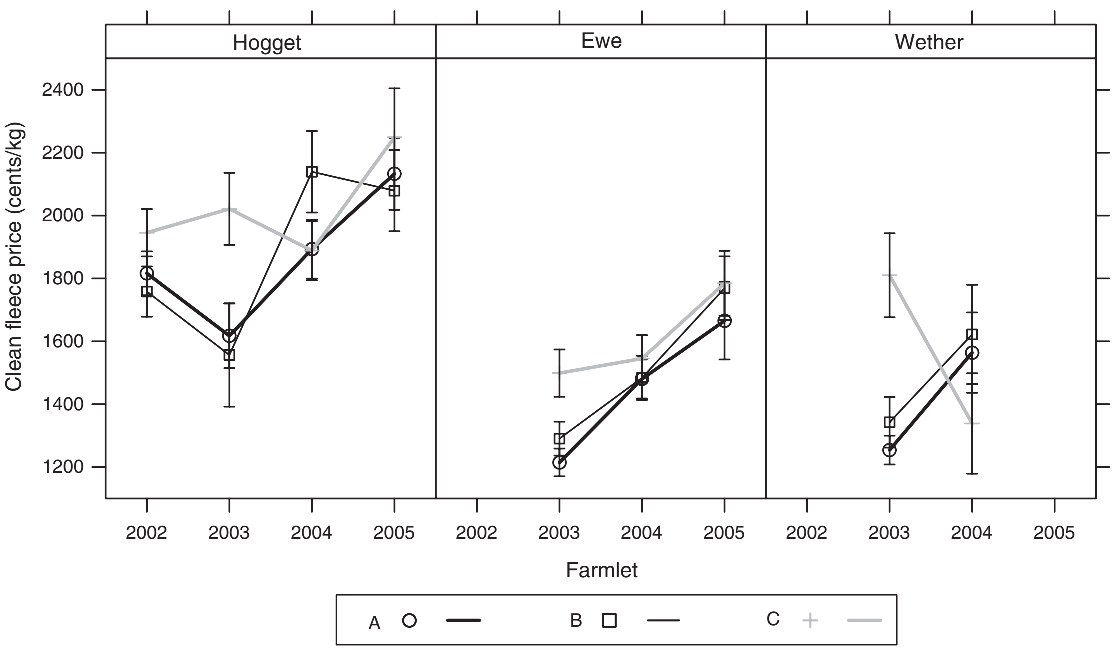

Fig. 3. Clean fleece price (cents/kg) (±95% confidence interval) for hoggets, ewes and wethers on farmlets A, B and C from 2002 to 2005.

farmlet A had higher levels of soil P, legume herbage, green digestible herbage and supplement fed compared with the other farmlets (B and C). In relation to the proportion grazed, farmlets A and B were similar but much higher than that of farmlet C due to the different grazing managements imposed. Thus, it may be deduced that the reason that fleece weight per head was higher on farmlet A was probably the greater levels of legume and/or green digestible herbage, which in turn were significantly correlated

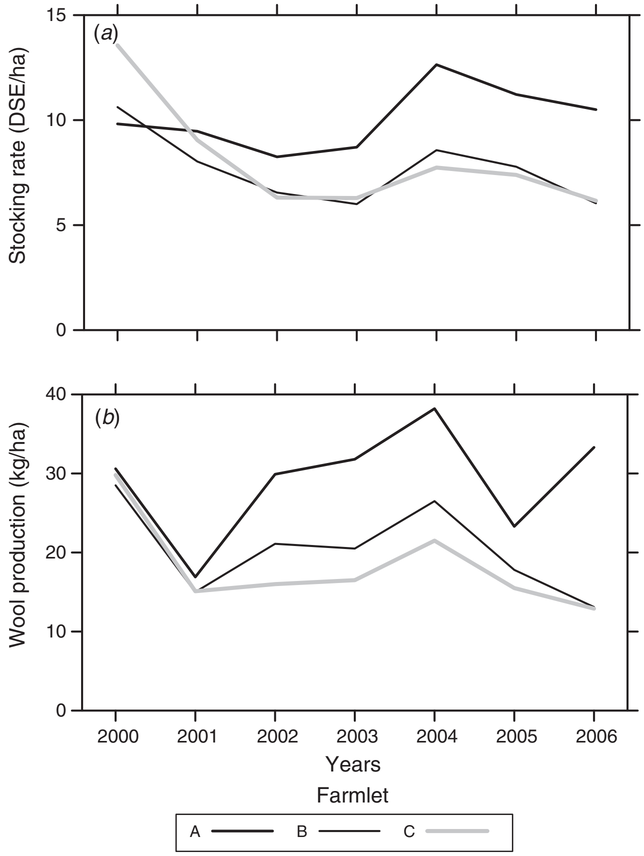

Fig. 4. (*a*) Average annual stocking rate (DSE/ha) across all three farmlets from 2000 to 2006 (Scott *et al*. 2013*b*) and (*b*) average greasy wool produced per ha on farmlets A, B and C from 2000 to 2006 adjusted to provide an estimate of wool production assuming all livestock were sheep (by dividing average values per farmlet by the proportion of total stocking rate made up by sheep on each farmlet).

Table 4. Total wool income per ha and per farmlet calculated from 2003 to 2005 for farmlets A, B and C

Year	Total wool income ($/ha)			Total wool income ($/farmlet)		
	A	B	C	A	B	C
2003	236	154	142	12 550	8201	7455
2004	386	263	203	20 496	13 965	10 638
2005	286	228	195	15 209	12 118	10 253
Average	303	215	180	16 085	11 428	9449

with soil P (Guppy *et al*. 2013) and, later in the trial, by the increased levels of supplementary feeding. By similar reasoning, it appears that the generally lower average fleece weight per head on farmlet C compared with the control farmlet (B), was due to the much lower proportion of farmlet C grazed on any one day, a characteristic of intensive rotational grazing, as farmlets B and C were similar in legume herbage, green digestible herbage, stocking rate and level of supplement fed.

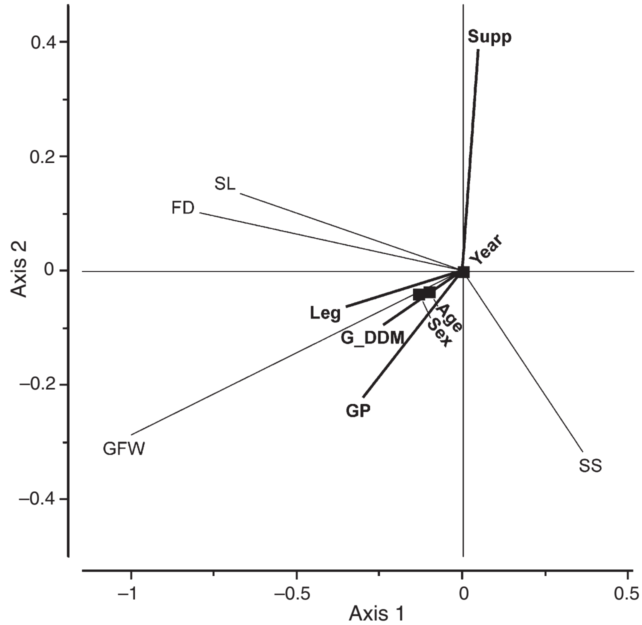

Fig. 5. Biplot from RDA analysis showing response variables of GFW, FD, SL and SS (thin lines) and explanatory continuous variables (thick lines) supplement (Supp), grazed proportion (GP), legume herbage (Leg) and green digestible herbage (G_DDM) and nominal variables (squares) Sex, Age and Year. The relationships are explained mostly by axis 1 (89%) and to a lesser extent by axis 2 (9%). (Acute angles between lines indicate positive correlations whereas those close to 180° apart are strongly negatively correlated; angles of ~90° indicate that variables are not correlated with each other).

Discussion

Greasy fleece weight

There were significant differences in GFW per head between two or more of the farmlets in every year after 2001. GFW, stocking rate and bodyweight (Hinch *et al*. 2013*a*) have shown significant differences across the three farmlet treatments and this reflects the significant differences between farmlets reported by others in pasture botanical composition (Shakhane *et al*. 2013*b*), pasture quality and quantity (Shakhane *et al*. 2013*a*) and soil fertility (Guppy *et al*. 2013). While the finding that wool production is enhanced by pasture quality and soil fertility and affected by grazing management is not new, we contend that demonstrating significant differences at the scale of these investigations within this complex, agroecosystem farmlet experiment, provides more credible evidence for livestock producers, the main stakeholder audience of this Project, than research conducted in small plots within less complex experiments.

The findings of this farmlet trial are consistent with the work of Hamilton (1975) who, in the same region, found that wool production was promoted by species which are able to remain green in winter, especially when the levels of green herbage could be maintained above the critical level of 500 kg DM/ha. In an experiment with Merino wethers on a phalaris and subterranean clover pasture, Willoughby (1959) found that grazing systems that allowed even small increases in green

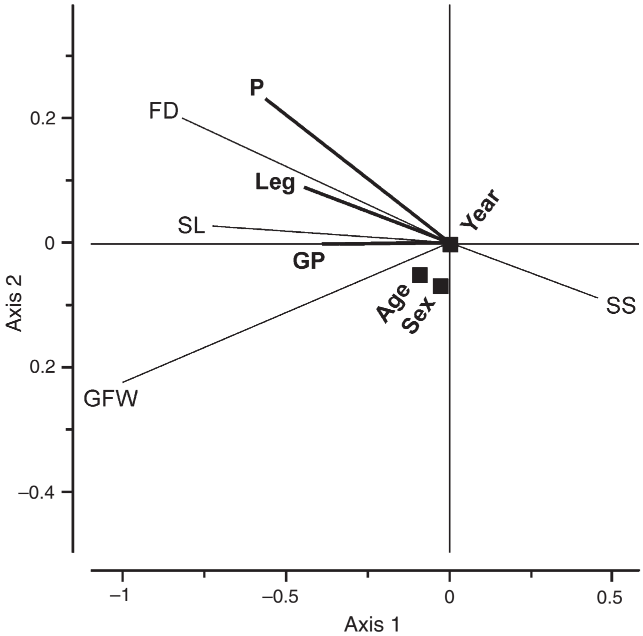

Fig. 6. Biplot from RDA analysis showing response variables of GFW, FD, SL and SS (thin lines) and explanatory continuous variables (thick lines) phosphorus (P), legume herbage (Leg) and grazed proportion (GP) and nominal variables (squares) sex, age and year. The relationships are explained mostly by axis 1 (94%) and to only a minor extent by axis 2 (4%). (Acute angles between lines indicate positive correlations whereas those close to 180° apart are strongly negatively correlated; angles of ~90° indicate that variables are not correlated with each other).

pasture during winter resulted in large increases in both liveweight and wool production. He also found that sheep production continued to respond to increases in green herbage mass up to a maximum of 1500 kg DM/ha, above which livestock production levelled off. It is noteworthy that this level of green herbage was reached on only one brief occasion. During most of the trial period, levels of green herbage were substantially lower (Shakhane *et al*. 2013*a*) than 1500 kg DM/ha, suggesting that animal production was constrained below the maximum potential growth rate for much of the trial. Willoughby (1959) also found that higher liveweights and wool production per head were associated with grazing management systems that were closer to continuous grazing than rotational systems.

In a grazed trial on the Northern Tablelands, Whalley *et al.* (1976) found that white clover presence was linked to both stocking rate and superphosphate rate and that wool production per ha was higher when fertiliser had been used; a similar finding was found for farmlet A in this experiment. Lodge *et al*. (2003), on the North-West Slopes of NSW, also found that wool production per head was higher when subterranean clover was a component of the pastures. In addition, Curll (1977) found that increases in available pasture brought about by superphosphate applications, resulted in increased wool production and liveweight per head as well as higher reproduction rates and gross margins.

Research in Central Victoria by Warn *et al*. (2002) found that a system which received high soil P rates (25 kg P/ha.year) on 10-year-old sown perennial pastures and which was grazed intensively for short periods (with rest periods from 20 to 70 days depending on the recovery rate of the main perennial grass, phalaris), was able to support a high stocking rate of wethers, which produced up to 115 kg greasy wool/ha with little change in wool production per head or in FD. By comparison, the maximum amount of wool produced per ha in this farmlet trial was 38.2 kg on farmlet A in 2004, which is well below levels reached in more productive wool-growing regions. More recently, Victorian research has shown that the sowing of upgraded pastures and increases in soil fertility allowed significantly higher wool cuts per head and per ha, slightly higher FD, similar SS, higher carrying capacity and gross margin compared with typical pastures fertilised at a lower level (Saul *et al*. 2011). Carter and Day (1970) found that stocking rate was much more important than fertiliser rate in influencing wool production and value. However, as stocking rate increased, fertiliser became a more important contributor to pasture production and wool production and value.

Wool quality characteristics

The significantly lower FD observed on farmlet C sheep in some years increased the wool value per kg but the lower production meant that the fleece values per sheep were similar between farmlets. This is consistent with results reported by Adams and Oldham (1998) who found, compared with grazing systems with longer graze and shorter rest periods, that intensive grazing management increased wool value, but with lower production of wool per head and per ha.

It is noteworthy that SS did not play a large role in the value of wool produced from this experiment as the values were generally above critical levels. Thus, the effect of SS used in the price equation was relatively minor. Although any choice of price grid or equation for wool price can be criticised, the physical wool attributes described here will enable the re-analysis of wool values by others in the future.

Fibre diameter profiles

Creating a FDP which is representative of a group of sheep run under the same conditions can be difficult due to variation in FD between sheep, between staples and between individual fibres. The length variation and growth rate differences between fibres and staples can also impact on FDP. Sheep within a mob also have differing SL making it difficult to set a length to represent the whole flock. Also, operator skill levels in using the OFDA2000 can affect the accuracy of SL measurements (Marler *et al*. 2002).

The shape of the FDP was found to be similar between farmlets indicating that FD increased over the first few months after shearing, at a time of increasing feed availability. Jackson and Downes (1979) also reported increases in FD along the profile during the period of highest feed availability in spring–summer on the Northern Tablelands with its increasing temperatures and daylengths.

FDP differed substantially between individual sheep and the data followed no set parametric shape. Therefore, non-parametric curve fitting techniques were used. The use of B-splines to fit the profile allowed curves to be fit as close to the data as possible and has the advantage that this procedure provided the ability to

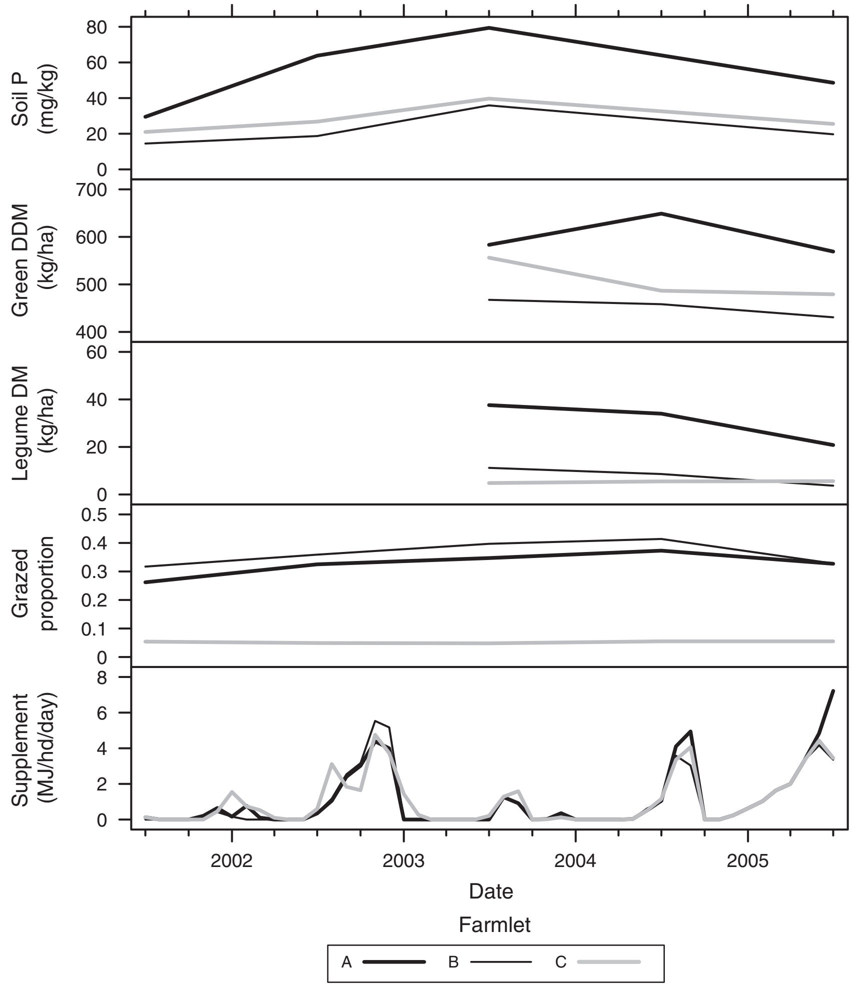

Fig. 7. Changes in the covariates which significantly affected fleece weight per head, fibre diameter, staple length and staple strength of flocks on farmlets A, B and C: soil phosphorus (Colwell P), green digestible herbage (Green DDM), legume herbage (Legume DM), grazed proportion and supplement fed per head per day.

make statistical comparisons at points along the profile thus avoiding the need to compare complete profiles as occurs with other approaches such as linear regression (Jackson and Downes 1979) or fitted cubic splines (Brown *et al*. 2000*a*; Brown and Crook 2005). This is potentially useful as comparisons can be made of FDP according to time and specific management events. The B-splines allowed differences to be examined both on an individual sheep basis as well as on a group basis. The differences in profiles between the three farmlets were probably the result of differences in grazing management as farmlet C differed significantly from both of the other farmlets in FDP characteristics and yet the level of inputs and stocking rates of farmlets B and C were similar. Although grazing management appeared to be the main cause of the differences, the higher quality of green pasture on farmlet A (Shakhane *et al*. 2013*a*) was also likely to have had an effect by increasing FD more than occurred on farmlet B.

Creating a single FDP profile from many individuals FDP which represents particular mobs or groups of sheep could allow producers to see how their stock have reacted to certain conditions over the year and revise management strategies appropriately (Gloag and Behrendt 2002). The group curves for farmlet C displayed a significant difference to farmlets A and B both as a whole curve and at most measured points where a B-spline had been fitted. This showed that the different management strategies had a significant effect on the FDP. This is consistent with Gloag *et al*. (2004) who found that intensive rotational grazing resulted in a finer FDP compared with set stocking and a simple rotational grazing treatment.

From dye banding, the last period of measurement was found to have the slowest growth rate and this coincided with the point of minimum FD. In all treatments, the point of minimum FD was at the end of the profile, near shearing time in late winter (August), the period when pasture quality and quantity were at a minimum on the farmlets (Shakhane *et al*. 2013*a*). There were few breaks in the tip section however 35% of breaks occurred in the mid-section of farmlet C and 18 and 14% for farmlets A and B, respectively. Fibre diameter was generally lower for farmlet C, but the SS was sometimes higher and the minimum point in diameter was at the base of the staple in the FDP, which would mean that it was within the jaws of the ATLAS for the SS measurement. Thus staples could be expected to naturally break more towards the middle of the staple.

The average range between minimum and maximum FD in the FDP was quite small for all the farmlets and this was reflected in the relatively high SS values. The FD range for farmlets A, B and C was 3.8, 3.4 and 3.1 μ while the average SS was 45.0, 45.7 and 43.3 N/ktex, respectively. In contrast, sheep in a more variable Mediterranean environment were found to have a variation in FD of 7.5 μm and a corresponding SS of 24 N/ktex (Hansford and Kennedy 1988).

Although there were differences between farmlets in wool cut and quality parameters for hoggets in most years, by 2005, these differences had disappeared. This is thought to have been due to the higher stocking rate on farmlet A at that time compared with the other farmlets and also to the shorter grazing rest periods adopted on farmlet C over time in an effort to improve animal liveweights (Scott *et al*. 2013*b*).

The relative values of wool produced per farmlet are consistent with the whole-farmlet profitability results in a related paper by Scott *et al*. (2013*a*) who showed that farmlet A had the highest wool returns due to higher GFW and stocking rates. As expected, stocking rate had a large influence on the gross wool income per ha. The influence of higher fleece weights and a higher carrying capacity on farmlet A meant significantly higher profitability at the whole-farmlet level in most years. The effects on cash flow of the higher costs of pasture renovation and fertilising on farmlet A and of the greater investment in fencing and water infrastructure on farmlet C have been described in a related paper by Scott *et al*. (2013*a*).

This paper has focussed on the impacts of three different whole-farmlet management systems on a range of wool quantity and quality traits, including FDP and income. While acknowledging that the results from an unreplicated farmlet experiment do not permit an assessment of experimental error equivalent to more traditional replicated experiments (Murison and Scott 2013), we nevertheless infer that the differences we have observed are far more likely to have been brought about by farmlet treatment than by random chance. Thus, we contend that hypothesis 1 (higher rates of pasture renovation and of soil fertility will result in higher per head and per ha wool production) was found to be true while hypothesis 2 (intensive rotational grazing will result in higher per ha production of wool, while improving wool quality through SS and/or lower FD) was proven false for the years of the trial and for the wool price relationships used.

Acknowledgements

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