Small Ruminant Research 157 (2017) 14–22

Contents lists available at ScienceDirect

Small Ruminant Research

journal homepage: www.elsevier.com/locate/smallrumres

Prediction of fleece insulation after shearing and its impact on maintenance energy requirements of Romney sheep

D.J. Cottle[a,*], D. Pacheco[b]

[a] 'Murrulla', Armidale, NSW, 2350, Australia
[b] Grasslands Research Centre, AgResearch, Palmerston North, 4442, New Zealand

ARTICLE INFO

Keywords:
ME requirements
Sheep
Coat depth
Fleece length
Seasonality
Insulation

ABSTRACT

Calculation of the maintenance metabolisable energy (ME) requirements should include the additional ME required to counteract heat loss in cold conditions if ambient temperatures occur below the lower critical temperature (LCT) of sheep. This correction requires an estimate of the fleece length of sheep during the year. Equations are presented to estimate the monthly fleece length of Romneys assuming different patterns of seasonality of wool growth, month of shearing and total fleece length. These lengths are discussed in the context of predicted levels of fleece insulation, which in turn influence sheep energy requirements under New Zealand climatic conditions. Predicted fleece insulation varied from 1 to 8 °C m^2 d/MJ in different months. The additional maintenance ME requirements of ewes are predicted for each month following shearing for different months of shearing. An example calculation resulted in an estimated additional 30% of ME being required when the average daily ambient temperature in the month of shearing was 5 °C below the LCT.

1. Introduction

Sykes (1982) stated that sheep fed above maintenance with over 2.5 cm wool cover are unlikely to be adversely affected by low environmental temperatures in New Zealand (NZ). However, Nicol and Brookes (2007) noted that the lower critical temperature (LCT) of sheep rises to 20 °C in the month immediately after shearing and the extra heat needed by a 60 kg ewe at 15 °C is equivalent to a 40% increase in metabolisable energy (ME) requirements for maintenance.

Gregory (1995) reviewed the use of shelter belts in NZ and argued that with wet and windy conditions, all sheep, except those fully fleeced, are probably exposed to temperatures below their LCTs. At shorter coat depths, LCTs are over 17 °C for most wind and rain combinations for sheep at maintenance (SCA, 1990; Gregory, 1995). For most grazed areas in NZ the mean monthly temperature is below 17 °C from April to November (NIWA, 2016; Vogeler et al., 2016) and the mean monthly minimum daily temperature is below 15 °C throughout the year with some locations not reaching 17 °C in any month. On average, one-third of days in NZ are wet (>1 mm rain) and wind speeds can be high (NIWA, 2016). All these climate factors increase LCT and therefore increase the likelihood that additional dietary energy is needed for sheep to maintain their core body temperature. These effects are likely to be exacerbated in lambs because of their smaller body radius (CSIRO, 2007) but we have focussed on adult Romney sheep which make up the majority of the NZ national flock. Cattle have a much larger body mass with higher internal tissue insulation than sheep, so their LCT is much lower (CSIRO, 2007) than ambient temperatures in NZ, so we have focused on sheep.

If cold ambient temperature occurs below the LCT of sheep, calculation of the ME requirements should include the additional ME required to counteract heat loss in the environmental conditions. Month of shearing is expected to have an effect on this as off shears sheep in winter would be expected to be more affected by cold than off shears sheep in summer. An algorithm to calculate the adjustment in ME for cold, wet or windy conditions is available (CSIRO, 2007). However, this algorithm requires an estimate of the fleece length of sheep during the year, which is not published in equation form for any sheep breeds, including seasonal, long wool NZ breeds such as the Romney, which are the main NZ sheep breed. Furthermore, experimental data on the seasonal growth of fleece is scarce. This paper provides such an equation developed from published observations, which then can be used to estimate the coat depth/fleece length of NZ Romney sheep in each month of the year for different levels of seasonality of wool growth, month of shearing and total annual fleece length. This provides a method of estimating the monthly coat depth value (the parameter F in the CSIRO, 2007 algorithm) for any sheep. An improved algorithm to adjust ME requirements would be useful for any sheep nutrition models or software tools that need to predict sheep ME requirements, such as

---

* Corresponding author.
E-mail address: adcottle@bigpond.com (D.J. Cottle).

http://dx.doi.org/10.1016/j.smallrumres.2017.10.004
Received 20 January 2017; Received in revised form 8 October 2017; Accepted 16 October 2017

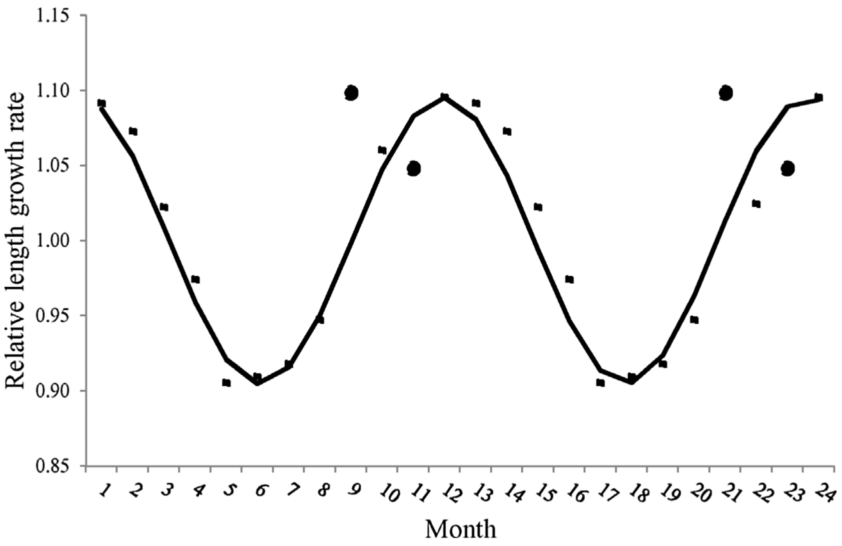

Fig. 1. Romney monthly fibre length growth rate fit to the data of Woods and Orwin (1988). Line is the fitted sinusoidal curve. Month 1/13 = January, Month 12/24 = December (Southern hemisphere). Amplitude is half of the range (maximum minus minimum) of values. The two excluded months from each year are shown as larger dots.

the NZ national inventory for greenhouse gases (Wear, 2013) among others.

2. Materials and methods

2.1. Seasonal fibre growth

Data for the daily fibre length growth rates of Romney sheep in each month (Woods and Orwin, 1988) were converted to the ratio of each month's fleece length growth rate to the yearly average growth rate (Fig. 1). As length growth rate was estimated by Woods and Orwin for every month, unlike seasonal fleece length data from grazing studies in the literature, this allowed monthly, sinusoidal curve parameters to be estimated. The sheep in the Woods and Orwin (1988) study had constant live weights (W) so the amplitude of the estimated sinusoidal curve would be expected to be lower than in grazing sheep, so the amplitude was subsequently adjusted by reference to grazing studies in the literature (see below).

The seasonality of the fleece growth was assumed to follow a sinusoidal curve of the form:

$$y = A*\sin(f.t + \varphi) + d \qquad (1)$$

which was fitted to the data (for 2 years) shown in Fig. 1 by least squares (using solver in Excel) to obtain parameter estimates for the amplitude (A), period (f), phase shift (φ) and vertical shift (d) of the relative monthly length growth rate (y) curve. Time (t) was expressed as number of the month in a year, with 1 and 13 being January and 12 and 24 being December. Data for two months of the year with the highest distance from the best fit curve were removed to improve the RMSE ($\sqrt{}$(observed-predicted)^2/n) of the revised equation.

To convert Eq. (1) to a general equation to predict the monthly length growth expected from any assumed yearly fleece length, the vertical shift parameter was multiplied by the ratio of yearly fleece length divided by 12 (i.e. average monthly length): mean annual value, to calculate a revised vertical shift parameter. The revised amplitude parameter was obtained by multiplying the revised vertical shift parameter by the seasonal amplitude expressed as a percentage (or proportion) of the original vertical shift value.

The ratio of fibre length growth between summer and winter (December and June in the Southern Hemisphere, respectively) was 1.19 (i.e. 9.5% amplitude) in the study of Woods and Orwin (1988). Other NZ studies have reported greater summer to winter wool length ratios of around 1.4 (e.g. Montgomery and Hawker, 1987; Hawker, 1985; Hawker and Littlejohn, 1989; Hawker and Thompson, 1987; Sumner and Bigham, 1993) when sheep have been in more typical commercial grazing conditions with fluctuating nutrition and live weights. Therefore the amplitude parameter used to calculate coat length in each month was assumed to be 19% (double that found by Woods and Orwin) to better match the ratios observed from the Hawker et al. studies, using the general equation.

2.2. Shearing month

The effect of shearing month was calculated by assuming that coat depth off shears (Dabiri, 1994; Dabiri et al., 1994, 1995, 2010) was 5 mm (cover combs) or 3 mm (standard combs) at the beginning of the month of shearing. The use of a cover comb, which leaves a greater depth of residual wool after shearing than the standard comb, increases the insulation value of the remaining fleece (Holmes et al., 1992).

Coat length at the beginning of each of the 11 months following shearing was calculated by adding the monthly length growth rate from the predictive sinusoidal equation for each preceding month to the length at the beginning of the preceding month:

$$\text{Length at beginning of month}_{x} = \text{Length at beginning of month}_{x-1} + \text{predicted growth rate in month}_{x-1} \qquad (2)$$

The total coat length, when the length grown in the 12th month following shearing was added to the coat length predicted at the beginning of the 11th month post shearing, was set equal to the assumed yearly fleece length. This assumed length was based on an average length of 150 mm of midside wool samples reported by Hight et al. (1976). A survey of staple length in non-second shear, crossbred sale lots from the north island (NZWTA, 2016) however found the average staple length was only 84 mm, so half the Hight et al. (1976) length (i.e. 75 mm) was also used in the modelling.

2.3. Fleece insulation

The effects of month of shearing, assumed yearly fleece length and seasonality of wool growth (i.e. amplitude) were studied by calculating results for fleece length at the beginning of each month using different assumed values in the predictive equation. The impact of coat depth of the animal on their external insulation against heat loss is predicted by CSIRO (2007) as follows:

$$I_e\ (^{\circ}\mathrm{C\,m^2\,d/MJ}) = [r/(r + F)][1/(0.481 + 0.326\,V^{0.5})] + r\ln[(r + F)/r](z\text{-}0.017\,V^{0.5}) \qquad (3)$$

Where

I_e = external insulation (fleece)
A = body surface area (m^2) = $0.09W^{0.66}$
r = radius of the animal (mm)
F = hair or fleece coat depth (mm)
V = wind velocity (km/h), and
z = thermal insulation/mm coat

CSIRO (2007) provided estimates of r and z derived from the work of Blaxter and colleagues in the 1960s, while V can be obtained from NIWA climate data (NIWA, 2016). There are no published values for r and z for NZ Romney sheep and we considered them unlikely to be very different from the reported CSIRO (2007) values. If NZ Romney parameter estimates became available they could be substituted into the deterministic equations used here. Thus F is the only factor for calculating I_e that does not have values provided in CSIRO (2007).

To account for rainfall, insulation (I_e) was multiplied by the correction factor 1–0.3(1-exp(-1.5 R/F)), where R = rainfall (mm/d) (CSIRO, 2007). NIWA (2016) data on the monthly pattern of rain at Darfield (1980–2010) was used to correct the insulation in each month by assuming 10 days in each month (1/3) receive the monthly rainfall/10. The rainfall correction factor for each month was thus 1/3 * (1-0.3(1-exp(-1.5 *R/F))) + 2/3.

The F values obtained in this paper for each month were obtained by calculating the average of the fleece lengths at the beginning of the month of shearing and the next month (or the average of the 11th month after shearing and annual length for the month before shearing) to calculate the coat depth in the middle of each month. These (middle month) lengths were input into Eq. (3) and multiplied by the rainfall correction equation derived from climate data for Darfield, Canterbury to obtain an I_e estimate provided by the fleece in each month using assumed expected values of r, z and V for sheep (CSIRO, 2007).

2.4. Cold stress

If the ambient temperature is below the LCT of sheep in any month, the calculated effect of lower external insulation (I_e, Eq. (3)) on the increase in ME intake to compensate for cold stress (E_{cold}) can be calculated from the CSIRO (2007) equation:

$$E_{cold}\ (MJ/d) = [A(T_{lc} - T_a)]/(I_t + I_e) \qquad (4)$$

Where A = body surface area (m^2), as above
T_{lc} = lower critical temperature (°C)
T_a = ambient air temperature (average)
I_t = (internal) tissue insulation = 1.3 (°C $m^2 d\ M\ J^{-1}\ cm^{-1}$)
I_e = external insulation (Eq. (3)).

The I_e and E_{cold} values were plotted against number of months after shearing and also fit to linear and non-linear (power and exponential) models with number of months after shearing and month of shearing as fixed effects, using Excel and JMP software (JMP 13, SAS Insitute, Cary, NC, 2016).

3. Results

3.1. Relative monthly fibre length growth

Analysis of the converted Woods and Orwin (1988) data, with two outlier monthly data points removed (September and November), are shown in Fig. 1 and yielded Eq. (5) with RMSE = 0.011, compared to an equation with a greater RMSE of 0.032 when all points were included:

$$FLG_{rel} = 0.10*\sin(0.53*\text{month number} + 1.40) + 1.00 \qquad (5)$$

where
FLG_{rel} = relative monthly fibre length growth relative to the annual growth.

Amplitude is half of the range (maximum minus minimum) of values. Eq. (5) can be converted to a general Eq. (6) for any assumed yearly fleece length and amplitude (as a percentage or proportion of the mean) as follows:

$$FLG = A * (FL/12) * \sin(0.53 * \text{month number} + 1.40) + FL/12 \qquad (6)$$

Where
FLG = monthly fibre length growth (mm)
A = amplitude as a percentage (or proportion) of the mean monthly fleece length
FL = annual fleece length (mm)
Month number = 1, 2…12 for January, February….December

Therefore an assumed yearly fleece length of 150 mm and an amplitude of 19% of the mean resulted in the equation:

$$FLG\ (mm) = 2.38 * \sin(0.53 * \text{month number} + 1.40) + 12.50 \qquad (7)$$

The predicted monthly length growth with amplitudes of 9.5% or 19% (Eq. (7)) of the mean are shown in Fig. 2.

3.2. Monthly coat depths

The coat depths at the beginning of each month, assuming shearing with cover combs at the beginning of the month, and a yearly fleece length of 150 mm are shown in Table 1 (19% amplitude).

Halving the assumed annual fleece length from 15 to 7.5 cm resulted in similar seasonal patterns (Table 2) of coat length, as expected.

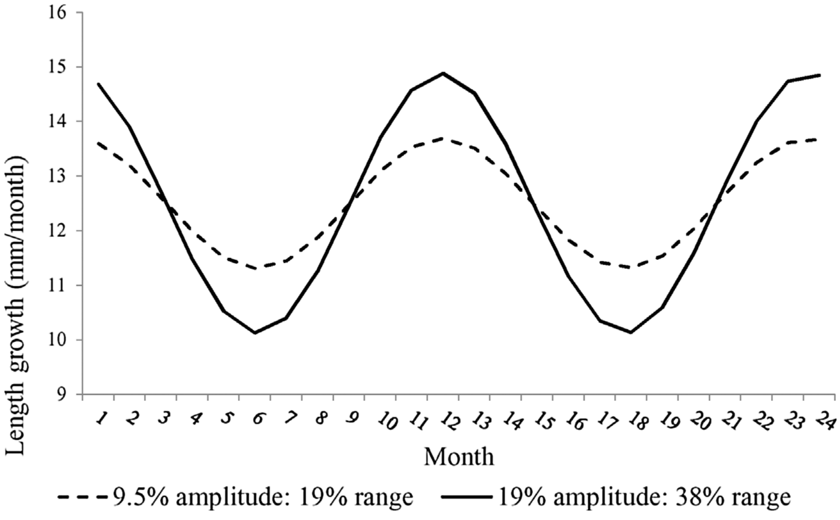

Fig. 2. Romney monthly fibre length growth rate assuming either an amplitude of 9.5% (Woods and Orwin, 1988) or 19% (Montgomery and Hawker, 1987) of the mean. Month 1/13 = January, Month 12/24 = December (Southern hemisphere).

Table 1
Estimated length of wool (mm) in each month of the year for different shearing months of Romneys, assuming a shorn fleece length of 150 mm and an amplitude of 19% of the mean.

	Wool length (mm) at beginning of month											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	5	20	34	47	58	69	79	89	100	112	126	140
February	140	5	19	32	44	54	64	75	86	98	111	125
March	126	141	5	18	30	40	50	61	72	84	97	111
April	113	128	142	5	17	27	37	48	59	71	84	99
May	102	117	131	143	5	16	26	36	47	59	73	87
June	91	106	120	133	144	5	15	25	36	49	62	76
July	81	96	110	123	134	145	5	15	26	38	52	66
August	71	85	99	112	124	135	145	5	16	28	41	56
September	60	74	88	101	113	124	134	144	5	17	30	45
October	48	62	76	89	101	112	122	132	143	5	18	33
November	34	49	63	76	87	98	108	119	130	142	5	19
December	20	35	49	61	73	84	94	104	115	127	141	5

Table 2
Estimated length of wool (mm) in each month of the year for different shearing months of Romneys, assuming a shorn fleece length of 75 mm and an amplitude of 19% of the mean.

	Wool length (mm) at beginning of month											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	5	12	19	26	32	37	42	47	53	59	65	73
February	73	5	12	18	24	30	35	40	45	51	58	65
March	66	73	5	11	17	23	28	33	38	44	51	58
April	59	67	74	5	11	16	21	26	32	38	45	52
May	53	61	68	74	5	10	15	21	26	32	39	46
June	48	55	62	69	75	5	10	15	21	27	33	41
July	43	50	57	64	70	75	5	10	16	22	28	36
August	38	45	52	59	64	70	75	5	11	17	23	30
September	32	40	47	53	59	64	69	75	5	11	18	25
October	26	34	41	47	53	58	63	68	74	5	12	19
November	20	27	34	40	46	52	57	62	67	73	5	12
December	12	20	27	33	39	44	49	55	60	66	73	5

3.3. Fleece insulation

The calculated fleece insulation in each month (based on the average length at the beginning of the shearing month and next month) assuming: an annual fleece length of 75 or 150 mm, a seasonality of 19%, r = 120, z = 0.141 (CSIRO, 2007), R = 5.3–7.5 mm/d and V = 11.3–14.6 (values for Darfield, Canterbury; NIWA 2016), is shown in Tables 3 and 4. Insulation is expressed in units per m^2 of fleece, so it is independent of the W or surface area (A) of the sheep.

3.4. ME requirements

The additional monthly ME requirements due to heat loss for a 60 kg ewe assuming a shorn fleece length of 75 or 150 mm, an amplitude of 19% of the mean and a difference of 1 °C between the sheep's LCT and ambient air temperature, with a constant (internal) tissue insulation factor of 1.3 °C m^2 d/MJ (CSIRO, 2007) using the E_{cold} Eq. (4) are shown in Tables 5 and 6.

The maintenance ME requirement (ME_m) of a 60 kg ewe, without the additional E_{cold} factor, is 9.79 MJ/d, consisting of 8.21 MJ/d for

Table 3
Estimated insulation of the fleece (°C m^2 d/MJ) in each month of the year for different shearing months of Romneys, assuming a shorn fleece length of 75 mm, seasonality amplitude of 19% of the mean, radius of 120 mm, coat insulation of 0.141 °C m^2 d/MJ/mm and rain and wind velocity at Darfield, Canterbury (average 6.3 mm/rainy day and 13.1 km/h respectively).

	Insulation (°C m^2 d/MJ)											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	0.86	1.37	1.82	2.33	2.68	2.97	3.35	3.59	3.66	3.97	4.28	4.52
February	4.63	0.85	1.33	1.84	2.20	2.51	2.90	3.16	3.27	3.59	3.92	4.29
March	4.41	4.68	0.83	1.34	1.73	2.06	2.45	2.73	2.89	3.23	3.57	3.94
April	4.09	4.49	4.70	0.86	1.27	1.62	2.02	2.32	2.52	2.87	3.23	3.62
May	3.79	4.20	4.54	4.97	0.83	1.21	1.61	1.94	2.17	2.54	2.92	3.31
June	3.51	3.92	4.28	4.82	4.96	0.81	1.22	1.57	1.84	2.23	2.62	3.02
July	3.24	3.66	4.02	4.56	4.83	4.91	0.83	1.21	1.52	1.92	2.32	2.73
August	2.95	3.38	3.75	4.29	4.57	4.78	5.02	0.83	1.18	1.59	2.01	2.44
September	2.63	3.07	3.45	3.98	4.27	4.50	4.87	4.91	0.80	1.23	1.67	2.11
October	2.26	2.72	3.11	3.64	3.94	4.18	4.55	4.73	4.58	0.82	1.28	1.73
November	1.85	2.32	2.73	3.25	3.56	3.81	4.19	4.39	4.38	4.55	0.83	1.29
December	1.37	1.86	2.29	2.81	3.14	3.41	3.79	4.00	4.03	4.33	4.51	0.80

Table 4
Estimated insulation of the fleece (°C m^2 d/MJ) in each month of the year for different shearing months of Romneys, assuming a shorn fleece length of 150 mm, seasonality amplitude of 19% of the mean, radius of 120 mm, coat insulation of 0.141 °C m^2 d/MJ/mm and rain and wind velocity at Darfield, Canterbury (average 6.3 mm/rainy day and 13.1 km/h respectively).

	Insulation (°C m^2 d/MJ)											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	1.12	2.08	2.90	3.78	4.38	4.86	5.49	5.86	5.96	6.44	6.91	7.35
February	7.53	1.10	2.01	2.91	3.56	4.10	4.74	5.17	5.35	5.86	6.37	6.92
March	7.12	7.61	1.06	2.00	2.72	3.31	3.98	4.47	4.73	5.28	5.82	6.40
April	6.63	7.23	7.65	1.08	1.87	2.53	3.23	3.77	4.11	4.70	5.29	5.90
May	6.17	6.80	7.32	8.07	1.03	1.76	2.49	3.10	3.52	4.15	4.78	5.41
June	5.73	6.38	6.92	7.76	8.06	1.00	1.77	2.44	2.95	3.62	4.28	4.95
July	5.29	5.96	6.53	7.37	7.78	7.97	1.03	1.77	2.37	3.08	3.79	4.48
August	4.83	5.52	6.11	6.95	7.38	7.69	8.16	1.03	1.74	2.50	3.26	3.99
September	4.30	5.03	5.64	6.49	6.94	7.27	7.84	7.98	1.01	1.84	2.65	3.42
October	3.68	4.45	5.10	5.95	6.42	6.78	7.37	7.62	7.44	1.05	1.94	2.76
November	2.95	3.77	4.46	5.32	5.82	6.22	6.81	7.10	7.06	7.40	1.07	1.96
December	2.09	2.98	3.73	4.59	5.14	5.57	6.18	6.51	6.54	6.98	7.33	1.02

basal metabolism plus 1.58 MJ/d for grazing energy expenditure (CSIRO 2007). The additional ME needed to combat heat loss in a cold environment (i.e. the values in Tables 5 and 6) per 1 °C difference between LCT and ambient temperature, expressed as a percentage of 9.79 MJ/d, are given in Tables 7 and 8 for the two assumed yearly fleece lengths.

The maximum difference of 6.3%–6.5% (75 mm) or 5.7%–6.0% ME/°C (150 mm) occurs, as expected, in the months of shearing (the diagonal of Tables 7 and 8). The increase in percentage of ME_m of 0.5%/°C from halving the assumed annual fleece length is small. The largest difference, equating to a 30% increase in ME_m for a 5 °C difference between the LCT and ambient temperatures in a 60 kg sheep, occurs when shearing is conducted in the coldest months of the year from May-October (NIWA, 2016).

3.5. Month of shearing effects

The patterns of insulation and E_{cold} in the months after shearing are shown in Figs. 3 and 4 assuming an annual fleece length of 150 mm.

The linear relationship between fleece insulation and months after shearing (Fig. 3) using the average insulation values for all months of shearing was:

Table 5
Estimated additional maintenance ME requirements (E_{cold}: MJ/d) in each month of the year for different shearing months of 60 kg Romneys, assuming a shorn fleece length of 75 mm, an amplitude of 19% of the mean and an ambient air temperature 1 °C below the sheep's lower critical temperature, with a constant tissue insulation factor.

	E_{cold} (MJ/d)											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	0.62	0.50	0.43	0.37	0.34	0.31	0.29	0.27	0.27	0.25	0.24	0.23
February	0.23	0.62	0.51	0.43	0.38	0.35	0.32	0.30	0.29	0.27	0.26	0.24
March	0.23	0.22	0.63	0.51	0.44	0.40	0.36	0.33	0.32	0.30	0.28	0.26
April	0.25	0.23	0.22	0.62	0.52	0.46	0.40	0.37	0.35	0.32	0.30	0.27
May	0.26	0.24	0.23	0.21	0.63	0.54	0.46	0.41	0.39	0.35	0.32	0.29
June	0.28	0.26	0.24	0.22	0.21	0.64	0.53	0.47	0.43	0.38	0.34	0.31
July	0.30	0.27	0.25	0.23	0.22	0.22	0.63	0.53	0.48	0.42	0.37	0.33
August	0.32	0.29	0.27	0.24	0.23	0.22	0.21	0.63	0.54	0.46	0.40	0.36
September	0.34	0.31	0.28	0.25	0.24	0.23	0.22	0.22	0.64	0.53	0.45	0.39
October	0.38	0.33	0.30	0.27	0.26	0.25	0.23	0.22	0.23	0.63	0.52	0.44
November	0.43	0.37	0.33	0.30	0.28	0.26	0.24	0.24	0.24	0.23	0.63	0.52
December	0.50	0.42	0.37	0.33	0.30	0.29	0.26	0.25	0.25	0.24	0.23	0.64

Table 6
Estimated additional maintenance ME requirements (E_{cold}: MJ/d) in each month of the year for different shearing months of 60 kg Romneys, assuming a shorn fleece length of 150 mm, an amplitude of 19% of the mean and an ambient air temperature 1 °C below the sheep's lower critical temperature, with a constant tissue insulation factor.

	E_{cold} (MJ/d)											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	0.56	0.40	0.32	0.26	0.24	0.22	0.20	0.19	0.18	0.17	0.16	0.16
February	0.15	0.56	0.41	0.32	0.28	0.25	0.22	0.21	0.20	0.19	0.18	0.16
March	0.16	0.15	0.57	0.41	0.33	0.29	0.25	0.23	0.22	0.20	0.19	0.17
April	0.17	0.16	0.15	0.56	0.42	0.35	0.30	0.26	0.25	0.22	0.20	0.19
May	0.18	0.17	0.16	0.14	0.58	0.44	0.35	0.31	0.28	0.25	0.22	0.20
June	0.19	0.17	0.16	0.15	0.14	0.58	0.44	0.36	0.32	0.27	0.24	0.21
July	0.20	0.18	0.17	0.15	0.15	0.14	0.58	0.44	0.37	0.31	0.26	0.23
August	0.22	0.20	0.18	0.16	0.15	0.15	0.14	0.57	0.44	0.35	0.29	0.25
September	0.24	0.21	0.19	0.17	0.16	0.16	0.15	0.14	0.58	0.43	0.34	0.28
October	0.27	0.23	0.21	0.19	0.17	0.17	0.15	0.15	0.15	0.57	0.41	0.33
November	0.32	0.26	0.23	0.20	0.19	0.18	0.17	0.16	0.16	0.15	0.57	0.41
December	0.40	0.31	0.27	0.23	0.21	0.20	0.18	0.17	0.17	0.16	0.16	0.58

Table 7
Estimated additional maintenance ME requirements in each month of the year for different shearing months of 60 kg Romneys, expressed as the percentage increase in the uncorrected maintenance ME requirements of 9.79 MJ/d, assuming the same parameters as in Table 5, for each degree ambient temperature is below the lower critical temperature (LCT).

	Percent increase in maintenance energy requirements per degree below LCT											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	6.3%	5.1%	4.4%	3.8%	3.4%	3.2%	2.9%	2.8%	2.8%	2.6%	2.5%	2.4%
February	2.3%	6.4%	5.2%	4.4%	3.9%	3.6%	3.3%	3.1%	3.0%	2.8%	2.6%	2.5%
March	2.4%	2.3%	6.4%	5.2%	4.5%	4.1%	3.7%	3.4%	3.3%	3.0%	2.8%	2.6%
April	2.5%	2.4%	2.3%	6.4%	5.3%	4.7%	4.1%	3.8%	3.6%	3.3%	3.0%	2.8%
May	2.7%	2.5%	2.3%	2.2%	6.4%	5.5%	4.7%	4.2%	3.9%	3.6%	3.3%	3.0%
June	2.8%	2.6%	2.5%	2.2%	2.2%	6.5%	5.4%	4.8%	4.4%	3.9%	3.5%	3.2%
July	3.0%	2.8%	2.6%	2.3%	2.2%	2.2%	6.4%	5.5%	4.9%	4.3%	3.8%	3.4%
August	3.2%	2.9%	2.7%	2.5%	2.3%	2.3%	2.2%	6.4%	5.5%	4.7%	4.1%	3.7%
September	3.5%	3.1%	2.9%	2.6%	2.5%	2.4%	2.2%	2.2%	6.5%	5.4%	4.6%	4.0%
October	3.8%	3.4%	3.1%	2.8%	2.6%	2.5%	2.3%	2.3%	2.3%	6.5%	5.3%	4.5%
November	4.4%	3.8%	3.4%	3.0%	2.8%	2.7%	2.5%	2.4%	2.4%	2.3%	6.4%	5.3%
December	5.1%	4.3%	3.8%	3.3%	3.1%	2.9%	2.7%	2.6%	2.6%	2.4%	2.4%	6.5%

Table 8
Estimated additional maintenance ME requirements in each month of the year for different shearing months of 60 kg Romneys, expressed as the percentage increase in the uncorrected maintenance ME requirements of 9.79 MJ/d, assuming the same parameters as in Table 6, for each degree ambient temperature is below the lower critical temperature (LCT).

	Percent increase in maintenance energy requirements per degree below LCT											
Shearing month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	5.7%	4.1%	3.3%	2.7%	2.4%	2.2%	2.0%	1.9%	1.9%	1.8%	1.7%	1.6%
February	1.6%	5.7%	4.1%	3.3%	2.8%	2.5%	2.3%	2.1%	2.1%	1.9%	1.8%	1.7%
March	1.6%	1.5%	5.8%	4.2%	3.4%	3.0%	2.6%	2.4%	2.3%	2.1%	1.9%	1.8%
April	1.7%	1.6%	1.5%	5.8%	4.3%	3.6%	3.0%	2.7%	2.5%	2.3%	2.1%	1.9%
May	1.8%	1.7%	1.6%	1.5%	5.9%	4.5%	3.6%	3.1%	2.8%	2.5%	2.3%	2.0%
June	1.9%	1.8%	1.7%	1.5%	1.5%	6.0%	4.5%	3.7%	3.2%	2.8%	2.5%	2.2%
July	2.1%	1.9%	1.8%	1.6%	1.5%	1.5%	5.9%	4.5%	3.7%	3.1%	2.7%	2.4%
August	2.2%	2.0%	1.8%	1.7%	1.6%	1.5%	1.4%	5.9%	4.5%	3.6%	3.0%	2.6%
September	2.4%	2.2%	2.0%	1.8%	1.7%	1.6%	1.5%	1.5%	5.9%	4.4%	3.5%	2.9%
October	2.8%	2.4%	2.1%	1.9%	1.8%	1.7%	1.6%	1.5%	1.6%	5.8%	4.2%	3.4%
November	3.2%	2.7%	2.4%	2.1%	1.9%	1.8%	1.7%	1.6%	1.6%	1.6%	5.8%	4.2%
December	4.0%	3.2%	2.7%	2.3%	2.1%	2.0%	1.8%	1.8%	1.7%	1.7%	1.6%	5.9%

$$\text{Insulation } (^\circ\text{C m}^2\text{ d/MJ}) = 0.86 + 0.60 * \text{number of months after shearing}, \; R^2 = 0.99 \quad (8)$$

The prediction expression from the linear model ($R^2 = 0.98$, RMSE = 0.29) using all data was:

Insulation (°C m^2 d/MJ) = 1.03 + shearing month (0, −0.13, −0.22, −0.26, −0.21, −0.10, 0.02, 0.17, 0.27, 0.29, 0.24, 0.13, for months 1–12 respectively) + months after shearing (0, 0.85, 1.63, 2.35, 3.03, 3.66, 4.25, 4.80, 5.33, 5.83, 6.30, 6.66, for months 0–11 respectively).

There were significant ($P < 0.01$) but very small (less than 0.3 °C m^2 d/MJ) differences in fleece insulation between months of shearing with April (month 4) shearing resulting in the lowest average insulation and October (month 10) the highest.

The non-linear, power relationship between E_{cold} and months after shearing (Fig. 4) using the average E_{cold} values for all months of shearing was:

$$E_{cold} \text{ (MJ/day)} = 0.\ 603 * \text{number of months after shearing}^{-0.558}, \; R^2 = 0.997 \quad (9)$$

The exponential relationship for all data points was:

$$E_{cold} \text{ (MJ/day)} = 0.\ 501 * (e^{-0.143 * \text{number of months after shearing}}), \; R^2 = 0.91 \quad (10)$$

There were significant ($P < 0.01$) but very small differences in the a coefficient (scale: 0.472–0.526) and b coefficient (rate: −0.131 to −0.156) terms in the exponential equations for E_{cold} for different months of shearing (Table 9), so month of shearing had a significant, but small impact on E_{cold} for all months after shearing.

The month of shearing with the highest scale value for E_{cold} was June and the lowest scale value resulted from January shearing. The month of shearing with the most negative exponential rate value (fastest rate of decline of E_{cold} for additional months after shearing) was September and the highest was February.

4. Discussion

4.1. Seasonality of wool growth

The two seasonal patterns assumed (9.5% versus 19% amplitude) made little (less than 5 mm) difference in the calculated monthly wool lengths for an annual fleece length of 15 cm. For any specific month, the largest difference was only 5 mm coat length in some months. A more pronounced seasonal pattern (greater amplitude) resulted in slightly shorter wool predicted in spring for sheep shorn earlier in the year and slightly longer wool predicted in autumn for sheep shorn later in the year. More importantly, when sheep are most susceptible to cold stress in the 1–2 months after shearing, when coat length is at its shortest, the effect of different levels of seasonality of wool production, expressed via fibre length, was close to zero (0–2 mm). Thus use of the higher level of seasonality (19%) expected in grazing sheep seemed reasonable for the insulation and E_{cold} modelling.

With an assumed shorter annual fleece (7.5 versus 15 cm), when sheep are most susceptible to cold stress in the few months after shearing, the effect of different levels of seasonality of wool production, expressed via fibre length, was also close to zero. Therefore, uncertainty in the estimation of the seasonality parameter is not likely to have a

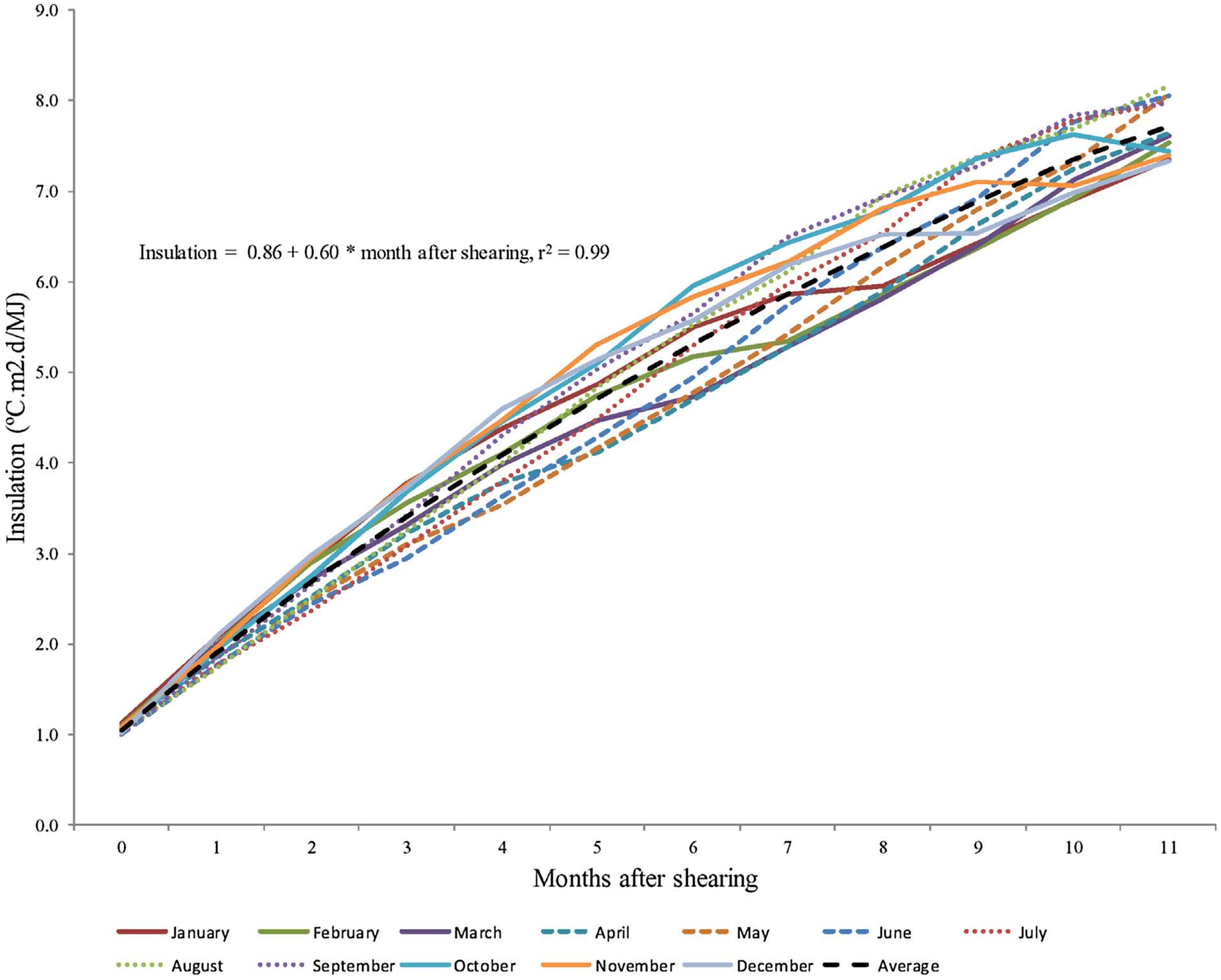

Fig. 3. Insulation of the Romney fleece for the months following shearing with different months of shearing.

large impact on the estimated insulation estimate if our approach is used to model fleece length. There are no recent papers documenting seasonal wool growth in NZ Romneys but if new seasonal fleece growth data became available in future the approach used in this paper could be used to generate new parameters for the various predictive equations.

It should be noted that the effect of seasonality is greater on fibre diameter (FD) and therefore fibre cross-sectional area ($\pi*(FD/2)^2$) than fibre length (L). Fibre mass is proportional to cross-sectional area multiplied by length. Cottle (1987) and Sumner and Bigham (1993) noted that the L to FD^2 ratio is fairly constant in individual Merino and Romney cross sheep respectively, with a proportional change in FD causing a greater increase in wool growth and/or fleece weight than the same proportional change in L. Woods and Orwin (1988) reported that the summer to winter ratio was 1.89 for fibre volume, 1.29 for FD and only 1.20 for L. Montgomery and Hawker (1987) observed that summer wool growth was 3–5 times higher than winter wool growth rate. Thus the seasonality of length growth rate in Romney based breeds is less than some may expect from seasonal wool growth rates.

4.2. Additional ME requirements due to cold

The insulation afforded by the fleece varied from 0.8 to 8.2 °C m^2 d/MJ (Tables 3 and 4). For a 60 kg sheep this would translate into an additional daily ME requirement of 0.14–0.64 MJ in different months (Tables 5 and 6) for every centigrade degree the ambient temperature was below the LCT, with the maximum occurring in the month of shearing, as expected. The maintenance ME increase for a 5 °C difference was calculated as 30% for both a 50 kg and 60 kg sheep. Nicol and Brookes (2007) noted that a 5 °C difference off shears between LCT and ambient temperature increased maintenance requirements of a 60 kg ewe by 40%. This is a similar outcome to our calculations, given that our calculated fibre length in the month of shearing was the average of the off shears length and the shearing month's length growth. That is, the insulation provided in the month of shearing in our calculations was not based simply on the (lower) off shears length (as calculated by Nicol and Brookes, 2007) which only occurs on the day of shearing. Fibre growth starts immediately post shearing and is continuous throughout each month.

As previously noted, there are many months of the year in NZ sheep grazing regions where the ambient temperature is expected to be at least 1 °C below the LCT of sheep. Thus the ME requirements of sheep will be greater than that predicted by models that do not include the E_{cold} term in their ME calculations. This is relevant to models that rely on estimates of ME requirements to calculate dry matter eaten by livestock, such as the NZ national greenhouse gas inventory (Wear, 2013) and OVERSEER (Wheeler, 2015), a software application supporting farmers to make informed decisions about their nutrient use on-farm, among others. In these two models, the emissions of methane or nitrogen (N) to the environment are functions of dry matter intake (DMI). For example, the inventory equations calculate methane emissions (tonnes/head/month) of adult sheep as DMI multiplied by an emission factor (20.9 g of methane per kg of DMI) (Wear, 2013), where DMI (kg DM/head/month) is calculated from total ME requirements divided by the feed ME content. Similarly, OVERSEER calculates the excretion of N to the environment as a function of N eaten, which is itself a function of

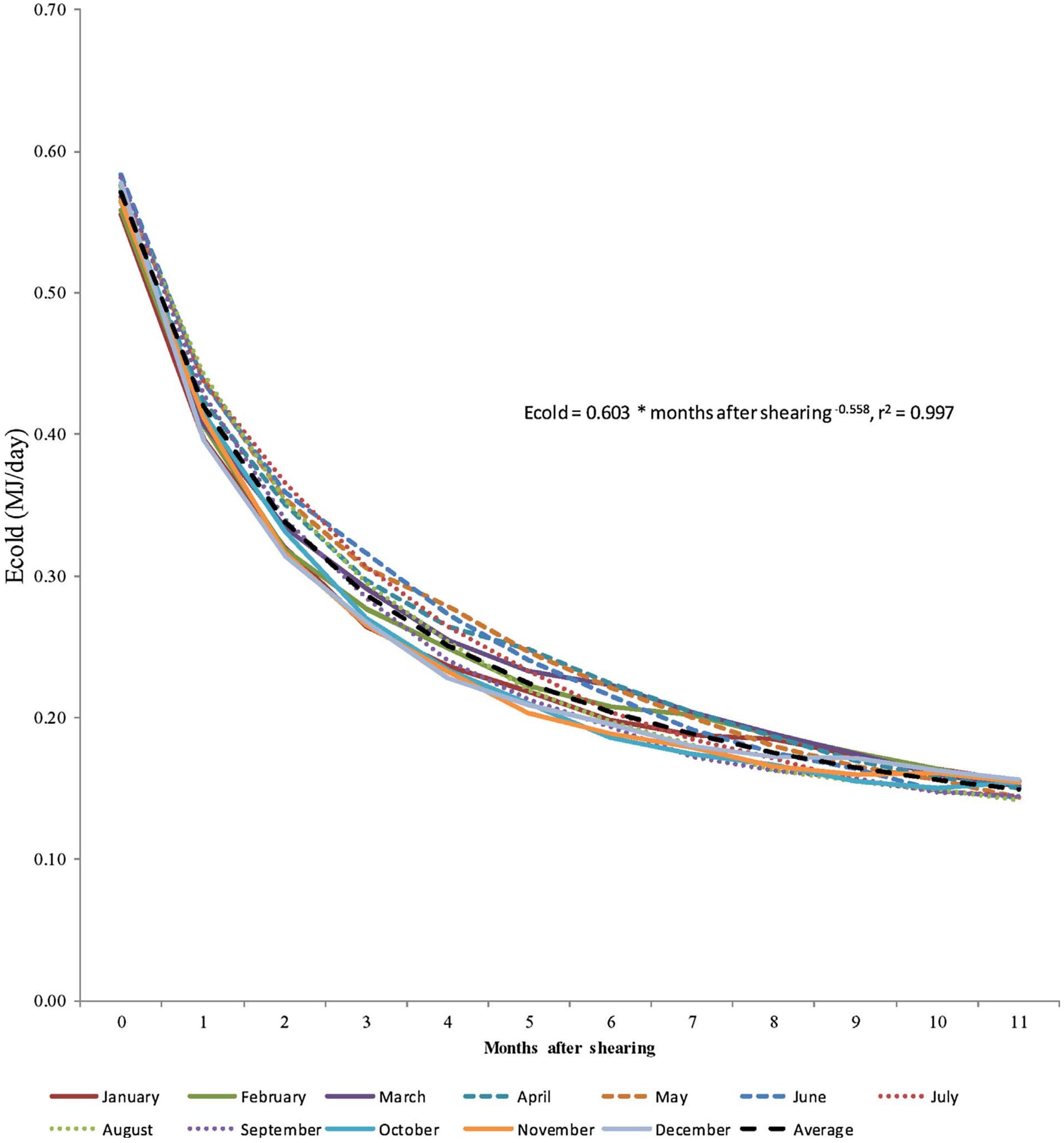

Fig. 4. Additional ME maintenance requirements (E_{cold}) of Romneys due to heat loss in the cold for the months following shearing for different months of shearing in Canterbury, New Zealand.

DMI and dietary crude protein concentration. Thus, for a given pasture ME content, methane or N emissions would be predicted to be higher if ME requirements are predicted to be higher due to heat loss in colder weather. The increased ME maintenance requirements would also impact on the emissions per unit of product ('emissions intensity') because less product (wool and meat) would be predicted to be produced from a given level of available energy in the pasture. The implications of the greater energy requirement for sheep reported on the estimation of feed intake and subsequent emissions of methane or nutrients to the environment deserve further attention.

We followed the practice of CSIRO (2007) and compared daily average ambient temperatures with LCT and did not attempt the more complex modelling of within day fluctuations in temperature and variable periods in the day below LCT. The impact of fluctuating temperatures and the validity of mean daily temperature when the standard deviation of daily temperature is high was studied by Giacomini (1979). Lambs exposed to a constant thermoneutral temperature (15 °C) were compared with lambs in fluctuating environments with a mean temperature of 15 °C. When fluctuations were from 10 to 20 °C, 5–25 °C, or 0–30 °C, feed intake was not different from constant 15 °C temperature. This suggests that using daily average temperatures is acceptable but we note that Freer et al. (2000) in their Technical Paper on the GrazFeed decision support tool calculated LCT for each 2-h period each day in relation to fleece insulation and the metabolic heat production per unit of surface area of the animal. The research area of fluctuating daily temperature deserves more study.

4.3. Month of shearing

The differences in predicted insulation and E_{cold} that result from different months of shearing were statistically significant but very small in size. The results are consistent with the conventional wisdom that shearing sheep in the coldest months of the year is not advisable unless sheep have access to adequate shelter (Sykes, 1982; Gregory, 1995).

Table 9
The exponential equations, E_{cold} = scale * exp (rate * number of months after shearing)) for different months of shearing with their standard errors.

Shearing Month	Scale	Rate
January	0.472 ± 0.031	−0.133 ± 0.017
February	0.478 ± 0.029	−0.131 ± 0.015
March	0.490 ± 0.027	−0.131 ± 0.014
April	0.501 ± 0.022	−0.133 ± 0.011
May	0.517 ± 0.021	−0.139 ± 0.011
June	0.526 ± 0.021	−0.145 ± 0.011
July	0.524 ± 0.021	−0.149 ± 0.011
August	0.522 ± 0.023	−0.154 ± 0.013
September	0.515 ± 0.028	−0.156 ± 0.015
October	0.499 ± 0.030	−0.152 ± 0.017
November	0.487 ± 0.032	−0.147 ± 0.018
December	0.484 ± 0.035	−0.144 ± 0.019

4.4. Management impacts

The ability to predict fleece length after shearing and the impact of this fleece length on insulation from the elements may improve the ability of livestock managers to generate feed budgets in a more accurate way. For example, one value of the equations described here is to provide an alternative to calculate the impact of low temperatures over the months following shearing in a more precise way than assuming a single value of a 40% increase in requirements (Nicol and Brookes, 2007). The maximum impact on insulation and therefore on animal ME requirements (6.0–6.5% increase in maintenance requirement per degree centigrade below LCT) shown in Tables 7 and 8 was, as expected, in the month of shearing. However smaller increases can be taken into account for the later months following shearing. The advent of real-time delivery of climate information to farmers via smartphones and other internet-connected devices means that information on wool growth and insulation could be used in practice to generate better estimates of ME requirements for farm feed budgets. Use of feed-budgeting software by NZ sheep farmers is increasing rapidly (Corner-Thomas et al., 2016), suggesting a growing need for accurate estimates of ME requirements of sheep. Although these authors did not report the type of software or the drivers for the increase, it could be speculated that some of the increase in software use could be associated with regulations on nutrient excretion to the environment (e.g. Barton, 2014). Inclusion of E_{cold} as a factor in the calculation of ME requirements via the equations described here should lead to the development of more accurate tools for both farmers when developing feed budgets and to regulatory bodies when developing regulations related to nutrient cycles on farms. Finally, a more accurate calculation of ME requirements will help meet welfare standards for animals post shearing.

5. Conclusion

Cold can have a significant effect on the maintenance energy requirements of NZ sheep in the month of shearing and in subsequent months. This paper provides a method of predicting the increase in maintenance ME requirements based on equations developed for predicting coat depth in every month based on the seasonality of length growth, annual fleece length and month of shearing. Breeds with less seasonal wool growth, like the Merino, would have a lower amplitude in the length growth equation. Any software models or tools which include maintenance ME requirements should include a heat loss correction factor for sheep, particularly in cold climates.

Conflict of interest

There are no conflicts of interest.

Acknowledgement

This work was conducted in parallel to a review of the effect of cold on the ME requirements of ruminants carried out by AgResearch for OVERSEER Ltd.

References

Barton, M.D., 2014. What farmers will need from scientists over the next 20 years under a resource-capped environment. Proc. N. Z. Soc. Anim. Prod. 74, 254–259.
CSIRO, 2007. In: Freer, M., Dove, H., Nolan, J.V. (Eds.), Nutrient Requirements of Domesticated Ruminants. CSIRO publishing, Collingwood, Victoria, Australia 270 pages.
Corner-Thomas, R.A., Kenyon, P.R., Morris, S.T., Ridler, A.L., Hickson, R.E., Greer, A.W., Logan, C.M., Blair, H.T., 2016. Brief communication, the use of farm-management tools by New Zealand sheep farmers: changes with time. Proc. N. Z. Soc. Anim. Prod. 76, 78–80.
Cottle, D.J., 1987. Fleece weight, fibre diameter ratios and sheep selection. Wool Tech. Sheep Breed. 35. pp. 186–189.
Dabiri, N., Parker, W.J., Morris, S.T., McCutcheon, S.N., 1994. Effects of pre-lamb and conventional full-wool shearing on the productivity of ewes. Proc. New Zealand Soc. Anim. Prod. 54, 223–226.
Dabiri, N., Parker, W.J., McCutcheon, S.N., Wickham, G.A., 1995. Productivity and cold resistance in ewes pre-lamb shorn by standard or cover comb. Aust. J. Agric. Res. 46, 721–732.
Dabiri, N., Morris, S.T., Wallentine, M., McCutcheon, S.N., Parker, W.J., Wickham, G.A., 2010. Effects of pre-lamb shearing on feed intake and associated productivity of May- and August-lambing ewes. NZ J. Agric. Res. 39, 53–62.
Dabiri, N., 1994. The effects of pre-lamb shearing on feed intake, metabolism and productivity of sheep. Ph.D. Thesis. Massey University, Palmerston North, New Zealand.
Freer, M., Moore, A.D., Donnelly, J.R., 2000. The GRAZPLAN animal biology model for sheep and cattle and the GrazFeed decision support tool. CSIRO Plant Industry Technical Paper. . www.grazplan.csiro.au/files/TechPaperMay12.pdf.
Giacomini, G.E., 1979. Effect of fluctuating temperature on lamb performance. M.Sc. Thesis. Kansas State University, Manhattan, USA.
Gregory, N.G., 1995. The role of shelterbelts in protecting livestock, a review. N. Z. J. Agric. Res. 38, 423–450.
Hawker, H., Littlejohn, R.P., 1989. Relationships between staple strength and other wool characteristics of Romney ewes. N. Z. J. Agric. Res. 32, 305–310.
Hawker, H., Thompson, K.F., 1987. Effects of pasture allowance in winter on liveweight, wool growth, and wool characteristics of Romney ewes. N. Z. J. Exper. Agric. 15, 295–302.
Hawker, H., 1985. Effects of season and nutrition on wool growth. In: Proceedings of Wool Production Seminars. New Zealand Wool Board. pp. 1–13 Chapter. 4.
Hight, G.K., Atkinson, J.J., Sumner, R.M.W., Bigham, M.L., 1976. Hill country sheep production. N. Z. J. Agric. Res. 19, 197–210.
Holmes, C.W., Kamil, K.A., Parker, W.J., Mackenzie, D.D.S., Purchas, G., Kidd, R., 1992. Effects of shearing method on the physiology and productivity of sheep. Proc. N. Z. Soc. Anim. Prod. 52, 199–202.
JMP, 2016. Nonlinear Regression with Built-In Models www.jmp.com/support/help/Nonlinear_Regression_with_Built-In_Models.shtml#313132.
Montgomery, G.W., Hawker, H., 1987. Seasonal reproduction in ewes selected on seasonal changes in wool growth. J. Reprod. Fert. 79, 207–213.
NIWA, 2016. Climate summaries https://www.niwa.co.nz/education-and-training/schools/resources/climate/summary. Accessed 10 August 2016.
NZWTA, 2016. Staple Length & Strength Measurement for Crossbred Wool. http://www.wrightwool.co.nz/site/woolmerchant/Merchants Staple Length and Strength Brochure.pdf.
Nicol, A.M., Brookes, I.M., 2007. The metabolisable energy requirements of grazing livestock. In: Rattray, P.V., Brookes, I.M., Nicols, A.M. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Occasional Publication No. 14, pp. 151–172.
SCA, 1990. Feeding Standards for Australian Livestock: Ruminants. Standing Committee on Agriculture. CSIRO, East Melbourne 266 pp.
Sumner, R.M., Bigham, M.L., 1993. Biology of fibre growth and possible genetic and non-genetic means of influencing fibre growth in sheep and goats a review. Livest. Prod. Sci. 33, 1–29.
Sykes, A.R., 1982. Shelter requirements of the new born lamb. Proc. N. Z. Soc. Anim. Prod. 42, 7–11.
Vogeler, I., Cichota, R., Beautrais, J., 2016. Linking land use capability classes and APSIM to estimate pasture growth for regional land use planning. Soil Res. 54, 94–110.
Wear, S., 2013. Detailed methodologies for agricultural greenhouse gas emission calculation Version 2. MPI Technical Paper No: 2013/27. Prepared for MPI by Dr Andrea Pickering May 2011, Revised for MPI by Simon Wear August 2013.
Wheeler, D.M., 2015. OVERSEER Technical Manual. Introduction. OVERSEER Management Services Limited, Wellington, NZ ISSN: 2253-461X.
Woods, J.L., Orwin, D.F.G., 1988. Seasonal variations in the dimensions of individual Romney wool fibres determined by a rapid autoradiographic technique. NZ J. Agric. Res. 31, 311–323.