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Application of a body condition score index for targeted selective treatment in adult Merino sheep – a modelling study

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Highlights

- Random selection of adult sheep to leave untreated can be an effective TST strategy
- It is not essential that sheep left untreated are in the highest body condition scores
- Selection by body condition score still important to identify animals at welfare risk
- High percentage of adult sheep can be left untreated over the drier months

Abstract

This study aimed to establish whether sheep flock production losses due to nematode (worm) infections are typically greater in mature sheep selected for anthelmintic treatment at random compared to sheep selected for treatment based on low (poorer) body condition score (BCS). The study also examined the proportion of sheep in flocks that could be left untreated before production losses became evident, and projected worm egg pasture contamination. Sheep were monitored at two experimental sites in Western Australia (Mediterranean climate). Sheep were stratified for BCS, liveweight and faecal worm egg count (WEC) and allocated into treatment groups (treated or untreated), with equal numbers for each. Liveweight, BCS and WEC measurements were taken on 6 occasions at Farm A and 10 occasions at Farm B. Comparisons of sheep production (liveweight and BCS change) and pasture contamination potential (WEC) were conducted by generating "virtual flocks" of varying proportions sheep untreated (10%, 20%, 30%, 40%, and 50% untreated). For the comparison of the selection mode of sheep for treatment, the untreated sheep were either selected at random, or as the highest BCS animals at the commencement of observations. Univariate general linear models with least square difference post-hoc tests were used to examine differences between flocks for liveweight, BCS and WEC, and regression analysis was used to examine relationships between BCS and WEC, and liveweight and WEC. No difference in body weights was observed between flocks with varying proportions of ewes notionally left untreated at Farm B, and until more than 30% were left untreated at Farm A. There was no difference in BCS between flocks with varying proportions of ewes left untreated at either site. At no point were there differences in cumulative liveweight change or BCS between selection methods (BCS versus random) where the same proportion of sheep in virtual flocks were left untreated, suggesting that effort committed to individual BCS assessment would be of no benefit under these circumstances except for identifying low BCS sheep at risk of falling below critical limits associated with health or welfare risks. No consistent relationship between WEC and BCS or bodyweight was observed, indicating that BCS selection would have no lesser or greater impact on worm pasture contamination compared to random selection. Summer treatments based on a random selection index (with a minimum BCS limit), with up to 30% of adult sheep untreated can be expected to delay the development of anthelmintic resistance, with minimal adverse effect on sheep health or production.

Keywords

Refugia, Anthelmintic resistance, Targeted selective treatment, Sheep, Nematodes

Introduction

The effectiveness of ruminant nematode control is increasingly compromised due to widespread resistance to anthelmintics worldwide (Wolstenholme et al., 2004; Kaplan and Vidyshankar, 2012). Anthelmintic resistance has been a significant problem in Australia for many years (Besier and Love, 2003), and in Western Australia the predominant ovine gastrointestinal nematodes (*Trichostrongylus* spp. and *Teladorsagia circumcincta*) have become increasingly difficult to effectively control. Resistance to the benzimidazoles and levamisole anthelmintics in several nematode genera is widespread, and macrocyclic lactone resistance in *T. circumcincta* is present on the majority of sheep properties (Playford, et al 2014).

The concept of ‘refugia’ has been the focus of considerable research into sustainable control strategies that aim to minimise the development of anthelmintic resistance by allowing a proportion of the worm population to escape treatment, and so ensure the survival of sufficient nematodes of susceptible genotypes to dilute the resistant individuals surviving treatment (Van Wyk, 2001; Jackson et al., 2009; Leathwick et al., 2009; Leathwick and Besier, 2014). One refugia-based strategy under development is Targeted Selective Treatment (TST) which restricts anthelmintic treatment either to the animals judged most likely to suffer significant production loss or health effects if not treated, while leaving others in the group unexposed to anthelmintics (van Wyk and Bath, 2002; Kenyon et al., 2009; Leathwick et al., 2009; Besier, 2012). Recent investigations into the TST concept for non-haematophagous nematodes in small ruminants have considered animal production traits, such as body condition score (BCS) and body weight, as indicators of which individuals in a flock are likely to benefit from anthelmintic treatments (Hoste et al., 2002; Leathwick et al., 2006; Cringoli et al., 2009; Greer et al., 2009; Stafford et al., 2009; Gaba et al., 2010; Cornelius et al., 2014).

In Australia, TST investigations have centred on the use of easily-applied criteria to indicate those sheep in large flocks which can be left untreated when anthelmintics are given, especially the use of BCS (Besier et al., 2010). Recent investigations in Western Australia demonstrated that mature sheep (ewes) in the lowest BCS showed a greater BCS response to treatment than their higher BCS counterparts where nutrition was low and worm burdens high (Cornelius et al., 2014). The study by Cornelius et al (2014) confirmed that BCS provides a simple (but effective) index for TST decisions and suggested a benefit in committing the effort required to select sheep on this criterion, as opposed to simple random selection, to minimise the possibility that some sheep in low BCS may escape treatment and suffer adverse consequences. Furthermore, Cornelius et al (2014) also indicated that selecting sheep for treatment on the basis of high faecal worm egg count (WEC) was not an appropriate index, as there was no consistent relationship between egg counts and production-based indices.

This study aimed to investigate the production and refugia consequences of using BCS as a treatment selection criteria in situations where non-haematophagous worm species (*Trichostrongylus* spp. and *T. circumcincta)* dominate and adult sheep carry worm burdens typically associated with sub-clinical parasitism. Three questions about use of BCS as a treatment selection index and TST worm control programmes were addressed. Firstly, are production losses due to parasitism (worms) in a mature sheep flock likely to be greater if the sheep are selected for treatment at random (no selection index) rather than based on low body condition score? Secondly, what notional proportion of these flocks could be left untreated before production losses become evident, and would these production losses differ in comparison to treating all animals in the flock? Finally, what are the consequences for worm egg pasture contamination in flocks where a proportion of animals are not treated, in recognition of the epidemiological effects of allowing continued worm egg excretion after flock treatment?

Materials and methods

The experiment was conducted according to the guidelines of the Australian Code of Practice for the Use of Animals for Scientific Purposes, with approval from the Animal Ethics Committees of both the Department of Agriculture and Food Western Australia, and Murdoch University.

Experimental sites

Two experimental sites were used: a commercial farming property (Farm A) located near Woodanilling, approximately 265 km southeast of Perth, Western Australia (August 2011 to March 2012), and a research station (Farm B) near Mt Barker, approximately 370 km southeast of Perth (July 2011 to May 2012). The region has a Mediterranean climate characterised by hot, dry summers and cool, wet winters, with a mean annual rainfalls of 460 mm and 730 mm for Woodanilling and Mt Barker, respectively.

Experimental design and animal management

Approximately 267 Merino wethers aged 3 years were selected at Farm A and 205 Merino ewes aged 3 years and over at Farm B. Sheep were individually identified with radio-frequency identification ear tags. Sheep were stratified for BCS, liveweight and WEC at the initial sampling occasion (Table 1) and allocated into treatment groups (treated or untreated), with equal numbers for each. The mean measurements at the initial sampling (Table 1) were BCS 2.3, liveweight 40 kg and WEC 85 eggs per gram (epg) for Farm A and BCS 2.5, liveweight 51 kg and WEC 91 epg for Farm B. There was no significant difference in BCS, liveweight or WEC between treatment groups at the start of the study for either site.

The ewes at Farm B commenced lambing in June 2011 (four weeks prior to the experiment start date) and had lambs at foot when the experiment commenced (Table 1). Lambs were weaned in October 2011.

Sheep were grazed as a single group at each site in paddocks with pastures predominantly of annual rye-grass (*Lolium* spp.), subterranean clover (*Trifolium subterraneum*) and capeweed (*Arcotheca calendula*).

Anthelmintic treatments

Sheep in the treated group were treated at each visit (ie, at approximately monthly intervals; Table 1) with long-acting moxidectin at 1 mg/kg of liveweight (Cydectin LA™, Virbac Australia). This interval was used to ensure continuous activity against all major nematode species, especially as a degree of macrocyclic lactone resistance was present on both farms. Sheep in the untreated group received no treatment.

Measurements

Sheep were weighed, assessed for BCS and faecal samples collected on five occasions at Farm A and nine occasions at Farm B after the initial sampling and treatment days (Table 1). Only five of the nine sampling occasions at Farm B were used in the analyses (Table 1) due to very low WECs in the untreated sheep from September to December. Body condition was measured using a BCS scale of one (thin) to five (fat) assessed by palpation of the lumbar vertebrae by a single experienced operator (Jefferies, 1961; Thompson and Meyer, 1994). Faecal samples were collected directly from the rectum of all sheep at each sampling occasion and WEC performed using a modified McMaster technique whereby 2 g of faeces were used from each sample and each egg counted represented 50 epg of faeces (Hutchinson, 2009). The genera of trichostrongylid nematodes present was determined using larval culture and differentiation performed on pooled faecal samples (Lyndal-Murphy, 1993; Hutchinson, 2009).

Experimental comparisons

Comparisons of sheep production (liveweight and BCS changes) and pasture contamination effects (WEC) were conducted using “virtual flocks” of varying proportions of treated and untreated sheep, to investigate firstly, the effect of different BCS selection method (random versus highest BCS left untreated) and secondly, the effects of treating different proportions (10-50%) of the flock. “Virtual flocks” were created by drawing animal numbers from the treated and untreated groups either at random or by choosing those in highest BCS to leave untreated. For the analyses, observations were set to span a standard time of 5 months for each site, when WEC were highest at each site (Farm A, November to March; Farm B, January to May). These analyses assumed that treatments were given at the commencement of observations on each property and effects measured at the end of the 5-month period of observations.

Flock scenarios included leaving 10%, 20%, 30%, 40% and 50% of sheep untreated out of a notional group of 120 (Farm A) and 100 (Farm B) sheep, with the untreated sheep selected from their respective site groups at random, using the simple random number generator in PopTools Excel (Hood 2010). For the comparison of the mode of selection of untreated sheep, two such “virtual flocks” were created for each percentage untreated, with the untreated sheep either selected at random, or as the highest BCS animals at the commencement of observations. For selection of the highest BCS animals, Farm A had 52% of untreated animals in highest BCS (2.5), which were randomly selected (via poptools) to be in the virtual flocks. Farm B had 30% of untreated animals in BCS 2.7+ which were randomly selected for the virtual flocks. For the 40% and 50% untreated virtual flocks at Farm B, extra animals were randomly selected from the ones in BCS 2.5, which made up 48% of the untreated group. Random selections were notionally taken 10 times and mean values for liveweight gain, BCS and WEC used for comparisons, and mean values used for statistical comparisons. Control groups were included with one flock of sheep with all animals treated (0% untreated) and one flock of sheep with none treated (100% untreated).

Statistical Analysis

Liveweight change between sampling occasions was analysed as the percentage change based on liveweight change relative to initial liveweights at the start of each respective period. Univariate general linear models with least square difference post-hoc tests were used to examine differences between flocks for liveweight, BCS and WEC at sampling plus weight change and BCS change between sampling occasions, both for comparisons between flock selection methods and the effects of different percentages of sheep left untreated. Worm egg count data was log transformed for analyses using Log10 (WEC+25). Regression analysis in Microsoft Excel 2010 (Microsoft Corporation, USA) was used to examine relationships between BCS and WEC, and liveweight and WEC, using data from all untreated sheep from all sampling occasions in one analysis. All other analyses were conducted using SPSS Statistics Standard Version 22.0 (IBM Corporation, Ireland).

Results

Worm egg counts

The 5-month periods chosen for analyses spanned periods when pasture was seasonally dry (annual pastures) and high temperatures generally prevailed (late spring to summer at Farm A and summer to autumn at Farm B). At Farm A WEC were higher in untreated sheep compared with Farm B (P<0.001; Figure 1) with means over the observation period ranging from 138-1148 epg and 167-878 epg respectively. Treatment with moxidectin maintained low mean WECs at both Farm A (1 epg) and Farm B (2 epg) in the treated sheep over the observation period. WEC between treated and untreated sheep remained significantly different throughout the experiment for both farms (P<0.001).

The mean proportions of nematodes cultured by larval differentiation were *T. circumcincta* (13%), *Trichostrongylus* spp. (61%) and *Chabertia ovina* (26%) at Farm A, and *T. circumcincta (24%), Trichostrongylus* spp. (31%), *C. ovina* (7%) and *Haemonchus contortus* (37%) at Farm B. *H.contortus*-derived WEC at Farm B were below 1900 epg (determined as 37% of the highest WEC over the experimental period), suggesting that clinical haemonchosis was unlikely, and *T. circumcincta* and *Trichostrongylus spp.* were considered the major causes of production loss at both sites.

WEC relationship with BCS and liveweight

At Farm B there were weak positive relationships between WEC and BCS ($R^2 = 0.01$, P=0.003) and also between WEC and liveweight ($R^2 = 0.04$, P<0.001) in untreated sheep. This represented an increase in WEC of 132 epg over the range of BCS observed and 287 epg over the range of liveweight observed across the sampling periods. In contrast, at Farm A, a weak negative relationship was observed between WEC and BCS ($R^2 = 0.08$, P<0.001) representing a decline in WEC of 574 epg over the range of BCS observed. No relationship between WEC and liveweight was evident for Farm A.

BCS versus random methods for selection of sheep for treatment

There were no significant differences between virtual flocks with the same proportion treated but using a different selection method (random vs BCS) in regards to cumulative liveweight change, BCS change or WEC at either Farm A or Farm B (Table 2 and Table 3) over the whole experimental period, or for any individual sampling period (when analysed separately).

Effect of proportion of sheep treated and liveweight change

At Farm A, there was a difference in liveweight change (%) between the different virtual flocks (proportion treated) over the whole experimental period (P<0.001; Table 4), with a greater effect of worm infections (in comparison to 0% untreated) once 40% or more sheep were left untreated. Differences in liveweight change (%) between virtual flocks were evident between sampling periods 1-2 (P<0.001) and 2-3 (P<0.001).

At Farm B, there was no difference between the different virtual flocks (proportion treated) for liveweight change (%) over the experimental period as a whole or between sampling periods. The only differences observed were between sampling times 4 and 5, with the 100% untreated flock losing more weight than the 10% untreated (P=0.012) and 0% untreated flock (P=0.012) (Table 4).

Effect of proportion of sheep treated and body condition change

There was no difference in BCS change between virtual flocks (proportion treated) over the whole experimental period at either Farm A or Farm B (Table 4). Similarly there were no differences in BCS change between the virtual flocks (proportion treated) at either site between sampling periods, apart from a single instance at Farm A, specifically between samplings 3 and 4 where sheep in 0% untreated in comparison lost more BCS than sheep in 100% untreated groups (P=0.030; Table 4).

Effect of proportion of sheep treated and WEC

As expected, the WECs increased in the virtual flocks as the proportion of untreated sheep increased and this was significant at every sampling occasion ($P<0.001$, Table 5). The WEC also increased in each virtual flock between sampling occasions ($P<0.001$) at both sites.

Discussion

The key findings of this study were, that within the range of BCS observed, there was no observed benefit with respect to liveweight change, body condition change or WEC output when selecting sheep for TST based strategies using BCS compared with random selection; that there were no costs in terms of liveweight when up to 40% of sheep remained untreated or for body condition when 50% of sheep were untreated; and finally, WEC output (and therefore pasture contamination) increased as the proportion of untreated sheep increased.

The use of BCS as a TST selection index has been the subject of investigations in Australian regions where *T. circumcincta* and *Trichostrongylus* spp. are the major nematodes of sheep, and large flock sizes call for the timely and practical assessment of individual animals (Besier et al., 2010). This investigation extends previous evidence that BCS-based TST strategies can be applied simply in adult ewes in a Mediterranean-type environment, and are unlikely to cause adverse effects on sheep production if implemented when the worm larval intake rate is low. Furthermore, the observations suggest that random selection of animals can be used in implementing TST strategies, particularly when environmental conditions are such that larval development is also limited.

Measurements of animal production including weight gains in lambs have been shown to be appropriate indices for TST selection (Leathwick et al., 2006; Greer et al., 2009;

Kenyon et al., 2009) but these require multiple observations in order to identify changes over time. Further, the production performance of growing lambs may be at risk where frequent assessment is not possible, potentially resulting in the failure to identify the need for treatment at appropriate times. Hence, the TST strategy under investigation is intended specifically for mature animals, which are presumably immunocompetent and have developed some resilience to parasitic effects, and where short-term production changes are less significant.

No difference on BCS change or weight change was observed between the TST selection indices using either BCS (lowest BCS treated) or random selection of animals for treatment. Recent investigations observed that anthelmintic treatments provide a differentially-greater effect in low-BCS ewes in preventing further weight and condition decline (Cornelius et al., 2014), suggesting that BCS can therefore serve as an appropriate index for TST strategies. Earlier studies within this Mediterranean environment also utilised BCS as a TST selection index (Besier et al., 2010). However, while BCS assessment requires less effort than collecting weights or faecal samples, some effort is still required for performing individual lumbar palpations of each ewe to identify those in lowest BCS. Practicality of application is a key consideration for a TST selection index where total flock sizes are typically very large and labour availability is low (Besier, 2012). The present investigation therefore addressed the question of whether it is necessary to assess the ewes for BCS for treatment decisions, or whether the random selection of ewes would give a similar result in terms of flock production changes.

The modelling results in this investigation indicated no significant body weight or BCS differences when up to 50% of a “virtual flock” was left untreated when either BCS index or random selection of animals for treatment is used. This suggests that the time and effort committed to individual BCS assessment would be of no benefit under these circumstances. This outcome was based on *in vivo* data from flocks representative of commonly-occurring nutritional and parasitological situations observed in Mediterranean regions of Australia. However, given the results from previous work (Cornelius et al., 2014) it would be advised that sheep below a pre-determined BCS be included in the treatment group to minimise the risk of losses and compromised welfare in low-BCS sheep. The present studies also confirmed that substantial proportions of an adult ewe flock in good body condition could be left untreated without significant production loss, at least where environmental conditions that minimise re-infection from pastures are present. The appropriate TST proportion would vary with the nematode challenge and level of nutrition available. In this environment it appears that, provided sheep are in sound nutritional condition, a substantial proportion of an adult sheep flock may be left untreated without significant production loss.

No difference in body weights was observed between flocks with varying proportions of ewes notionally left untreated at Farm B, and until more than 30% were left untreated at the Farm A site. There was no difference in BCS between flocks with varying proportions of ewes left untreated at either site, although as expected, there was a trend towards a lower production loss where all sheep were treated compared with no sheep treated. No change in production effects was observed as the proportion of untreated sheep increased, and presumably this in part reflects the resilience of adult sheep in good body condition and adequate nutrition to parasitic effects (Walkden-Brown and Kahn, 2002; Kahn, 2003). This may also in part be related to the dry pastures during the observation period that were unlikely to yield significant numbers of infective larvae.

The observations were consistent with the earlier studies in Western Australia in which no significant adverse effect on wool growth or body weight change was observed in flocks where 50% or more of ewes were left untreated using BCS and the TST selection index (Besier et al., 2010). It was observed at Farm A that while BCS decreased, liveweight increased. Liveweight increases can reflect changes in factors other than body condition (muscle and fat) including increased weight of viscera and digesta (gut fill) reflecting changes in diet as well as time off feed and water at the time of measurement. Another contributor to weight but not body condition is fleece growth. For this reason BCS is considered a more direct measure of muscle and fat change than liveweight.

The findings of this investigation suggested WECs were not an appropriate TST treatment index in large flocks of adult sheep, even where individual WEC measurements were practicable. In both this study and a previous investigation where *T. circumcincta* and *Trichostrongylus* spp. also predominated (Cornelius et al., 2014), there was no consistent relationship between WEC and BCS or bodyweight. Treatments given only to sheep with highest WEC would therefore not benefit those sheep with low WEC but with reduced resilience to parasitism. The weak relationship between WEC and BCS also indicated that targeting higher BCS sheep to be left untreated would provide no greater reduction in flock WEC after treatment compared with random selection of sheep left untreated and hence no additional pasture contamination benefit. However, the remaining mean flock WEC after a targeted treatment can be easily estimated, and measures taken where it is considered excessive.

Results of earlier studies suggested that a BCS-based TST approach is likely to have particular application in Mediterranean environments in Australia, where routine strategic treatments in the hot and dry summer period contribute strongly to the development (both prevalence and severity) of anthelmintic resistance (Besier and Love, 2003; Playford et al., 2014). Also, earlier computer simulation modelling suggests that for a single treatment given in summer in this environment, leaving even a small percentage of adult sheep untreated can provide a significant amount of refugia for non-selected worms, hence delaying anthelmintic resistance (Dobson et al., 2011). In conjunction with those studies, results from this investigation suggest that summer treatments based on a random selection index (with a minimum BCS limit to identify animals at risk of disease or compromised welfare), with up to 50% of adult sheep untreated would be expected to significantly delay the development of anthelmintic resistance, with minimal adverse effect on sheep health or production. Whilst this study showed that leaving a proportion of sheep untreated increased flock WEC, the viability of larvae and contribution to refugia was not directly measured. Future studies could include direct measures such as pasture larval counts or tracer animals to approximate the contribution of untreated sheep to refugia in that specific environment.

Furthermore, while these TST strategies would be more applicable in locations where *T. circumcincta* and *Trichostrongylus spp*. are the major sheep nematodes, caution is needed if extrapolating the results from this investigation to different environments and circumstances. Further investigations in environments where worm challenge and nutritional levels differ, to account for differences in seasonal effects on pasture contamination with worm eggs, are required before blanket recommendations on this TST strategy can be made.

The analysis method by which virtual flocks were created from a pool of treated and untreated sheep could not account for possible differences in production effects over time due to pasture worm egg contamination effects after different flock proportions were treated. However, the between-month analyses suggested no effect of variable WEC output in this investigation, possibly due to the resilience of adult sheep to worm infections and because the observation period at each site spanned seasons when little worm larval development occurs in this environment (Woodgate and Besier, 2009). Nevertheless, TST strategies in environments with a lesser seasonal cessation in nematode larval development may have different outcomes, and as with all modelling approaches to nematode control, local validation is needed.

Conclusion

This investigation showed that for adult sheep in Mediterranean environments, it is possible to leave a substantial percentage of sheep untreated over the drier months without detrimental effects on production (liveweight and body condition). The greater the proportion of sheep left untreated, the greater the refugia is provided to delay the onset of drench resistance. This investigation demonstrated that over a period when infective larvae on pasture were minimal (due to dry seasonal conditions) up to 50% of a flock could be left untreated, and the selection of sheep to leave untreated based on low BCS was not essential, although this should still be considered to identify animals at risk of disease or compromised welfare. It is concluded that leaving a random percentage of adult sheep in good nutritional condition untreated in a Mediterranean environment can be an effective TST strategy.

Conflict of Interest

The authors declare that there is no conflict of interest. Meghan Cornelius was employed by pharmaceutical company Jurox Animal Health from January 2013 to February 2014 but the company had no input or influence on the investigation.

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Table 1. Experimantal events at experimental sites (Farm A and Farm B)

Farm A (wethers)			**Farm B (ewes)**		
Date	Event	Sampling occasion*	Date	Event	Sampling occasion*
-	-	-	June 2011	Lambing commenced	-
-	-	-	14 Jul 2011	Initial sampling/treatment	-
11 Aug 2011	Initial sampling	-	-	-	-
28 Sep 2011	Initial treatment	-	14 Sep 2011	Sampling	-
-	-	-	19 Oct 2011	Sampling and weaning	-
10 Nov 2011	Sampling	1	15 Nov 2011	Sampling	-
8 Dec 2011	Sampling	2	15 Dec 2011	Sampling	-
5 Jan 2012	Sampling	3	9 Jan 2012	Sampling	1
2 Feb 2012	Sampling	4	6 Feb 2012	Sampling	2
8 Mar 2012	Final sampling	5	7 Mar 2012	Sampling	3
-	-	-	10 Apr 2012	Sampling	4
-	-	-	8 May 2012	Final sampling	5

Sampling: Body condition score, weight, faecal sample for WEC, and treatment

Treatment: 1 mg/kg long acting moxidectin

*Sampling occasion included in analyses

Table 2. Change in liveweight (LWT) and body condition score (BCS) between the first and final sampling over a 5-month period comparing body condition score selection and random selection methods.

Untreated %	**Random**			**Low BCS**			**P value**
	First	Final	Change	First	Final	Change	
Liveweight change (kg)							
Farm A							
10%	50.0	53.0	3.0	50.1	53.1	3.0	ns
20%	50.1	52.9	2.8	50.1	52.9	2.8	ns
30%	50.0	52.7	2.7	50.0	52.6	2.6	ns
40%	50.0	52.6	2.6	50.0	52.4	2.4	ns
50%	50	52.4	2.4	50.1	52.3	2.2	ns
Farm B							
10%	61.6	61.9	0.3	62.0	61.9	-0.1	ns
20%	61.6	61.8	0.2	61.3	61.4	0.1	ns
30%	60.9	61.1	0.2	61.2	61.2	0.0	ns
40%	60.5	60.5	0.0	61.1	61.1	0.0	ns
50%	60.1	60.2	0.1	61.2	61.1	-0.1	ns
Liveweight change (%)							
Farm A							
10%	-	-	6.0	-	-	6.0	ns
20%	-	-	5.6	-	-	5.6	ns
30%	-	-	5.4	-	-	5.2	ns
50%	-	-	4.8	-	-	4.4	ns
Farm B							
10%	-	-	0.5	-	-	-0.2	ns
20%	-	-	0.3	-	-	0.2	ns
40%	-	-	0.0	-	-	0.0	ns
50%	-	-	0.2	-	-	-0.2	ns
BCS change							
Farm A							
10%	2.7	2.4	-0.3	2.7	2.4	-0.3	ns
20%	2.7	2.4	-0.3	2.7	2.4	-0.3	ns
30%	2.7	2.4	-0.3	2.7	2.4	-0.3	ns
40%	2.7	2.4	-0.3	2.7	2.4	-0.3	ns
50%	2.7	2.4	-0.3	2.7	2.4	-0.3	ns
Farm B							
10%	2.9	3.0	0.1	3.0	3.0	0.0	ns
20%	2.9	3.0	0.1	3.0	3.0	0.0	ns
30%	2.9	3.0	0.1	3.0	3.0	0.0	ns
40%	2.9	3.0	0.1	2.9	3.0	0.1	ns
50%	2.9	3.0	01	2.9	3.0	0.1	ns

ns = not significant (P>0.05)

Table 3. Worm egg count (eggs per gram) at final sampling between flocks at both sites, comparing selection based on body condition score (BCS) (highest score untreated) and random selection.

Proportion of flock untreated	**Farm A**			**Farm B**		
	Random	BCS	P Value	Random	BCS	P Value
10%	478	523	ns	251	221	ns
20%	685	915	ns	437	313	ns
30%	780	937	ns	520	543	ns
40%	884	1105	ns	630	621	ns
50%	970	1127	ns	712	718	ns

ns = not significant ($P>0.05$)

Table 4. Liveweight change (%) and body condition score (BCS) change between sampling periods for flocks with different proportions untreated at each site

	Sampling interval	**Proportion of flock untreated**							**P Value**
		0%[*]	**10%**	**20%**	**30%**	**40%**	**50%**	**100%**[#]	
Liveweight change									
Farm A	1-2	6.98^{a}	6.79^{ab}	6.58^{ab}	6.34^{ab}	6.20^{ab}	5.88^{b}	4.70^{c}	<0.001
	2-3	-1.92^{a}	-2.12^{a}	-2.29^{ab}	-2.67^{abc}	-3.01^{bcd}	-3.17^{cd}	-3.67^{d}	<0.001
	3-4	-2.18	-2.05	-2.08	-2.13	-2.11	-2.09	-2.09	ns
	4-5	3.59	3.65	3.73	3.99	4.08	3.98	4.17	ns
	Overall	6.15^{a}	5.98^{ab}	5.64^{ab}	5.20^{abc}	4.82^{bc}	4.35^{c}	2.79^{d}	<0.001
Farm B	1-2	-1.20	-1.24	-1.13	-1.21	-1.18	-0.98	-1.04	ns
	2-3	0.92	0.83	0.74	0.96	0.98	1.03	1.59	ns
	3-4	1.72	1.66	1.99	1.96	2.06	1.99	2.03	ns
	4-5	-1.26^{a}	-1.26^{a}	-1.49^{ab}	-1.73^{ab}	-1.90^{ab}	-1.88^{ab}	-2.23^{b}	ns
	Overall	0.05	-0.17	-0.05	-0.22	-0.22	-0.11	0.15	ns
BCS change									
Farm A	1-2	-0.04	-0.04	-0.04	-0.04	-0.03	-0.02	-0.04	ns
	2-3	-0.06	-0.04	-0.05	-0.04	-0.02	-0.05	-0.02	ns
	3-4	-0.30^{a}	-0.32^{ab}	-0.34^{ab}	-0.36^{ab}	-0.37^{ab}	-0.36^{ab}	-0.39^{b}	ns
	4-5	0.10	0.10	0.12	0.12	0.12	0.12	0.15	ns
	Overall	-0.28	-0.28	-0.28	-0.29	-0.28	-0.29	-0.31	ns
Farm B	1-2	0.15	0.13	0.12	0.11	0.11	0.13	0.11	ns
	2-3	-0.05	-0.05	-0.04	-0.03	-0.02	-0.05	-0.05	ns
	3-4	0.10	0.10	0.10	0.10	0.11	0.12	0.12	ns
	4-5	-0.14	-0.14	-0.12	-0.13	-0.15	-0.14	-0.13	ns
	Overall	0.06	0.05	0.07	0.06	0.06	0.07	0.07	ns

[*] 100% sheep in flock treated

[#] 0% sheep in flock treated

^{abcd} Values with different superscript within a row are significantly different (P<0.05)

ns = not significant (P>0.05)

Table 5. Mean flock worm egg counts (eggs per gram) at each sampling period between flocks of different proportions untreated at each site

Sampling period	Proportion of flock untreated							P Value
	0%[*]	10%	20%	30%	40%	50%	100%[#]	
Farm A								
1	0^{a}	62^{ab}	64^{b}	93^{c}	105^{cd}	116^{de}	137^{e}	<0.001
2	2^{a}	134^{b}	137^{b}	170^{bc}	186^{cd}	204^{d}	226^{d}	<0.001
3	0^{a}	233^{b}	242^{b}	307^{c}	339^{cd}	369^{de}	421^{e}	<0.001
4	5^{a}	369^{b}	381^{b}	477^{c}	529^{cd}	581^{de}	651^{e}	<0.001
5	0^{a}	673^{b}	705^{b}	794^{bc}	904^{cd}	984^{de}	1136^{e}	<0.001
Farm B								
1	0^{a}	42^{a}	73^{ab}	103^{bc}	123^{cd}	135^{d}	166^{d}	<0.001
2	0^{a}	115^{a}	180^{b}	244^{c}	271^{cd}	300^{d}	377^{e}	<0.001
3	2^{a}	200^{a}	326^{b}	443^{c}	472^{c}	552^{d}	660^{d}	<0.001
4	11^{a}	197^{a}	341^{b}	388^{b}	458^{c}	525^{d}	660^{e}	<0.001
5	4^{a}	248^{a}	426^{b}	522^{c}	629^{d}	713^{e}	873^{f}	<0.001

[*] 100% sheep in flock treated
[#] 0% sheep in flock treated
^{abcdef} Values with different superscript within a row are significantly different ($P<0.05$)
ns = not significant ($P>0.05$)

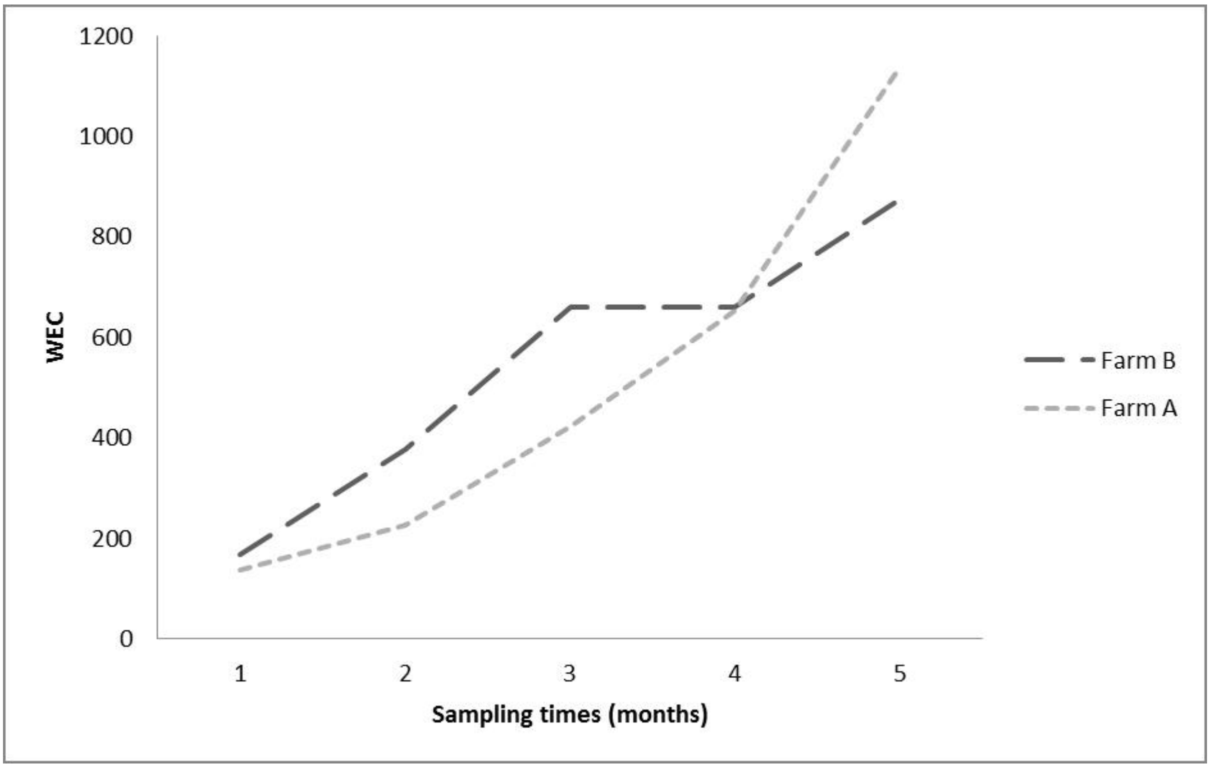

Figure 1. Mean worm egg counts in untreated sheep over the 5-month experimental periods at both sites (Farm A, November to March; Farm B, January to May).