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Effect of sire fecal egg count estimated breeding value on Katahdin lamb parasite resistance in pasture-based system

Andrew R. Weaver [a,1], Donald L. Wright [b], Scott P. Greiner [c], Scott A. Bowdridge [a,*]

[a] Division of Animal and Nutritional Sciences, West Virginia University, Morgantown, WV 26506, USA
[b] Southwest Agriculture and Research and Extension Center, Virginia Tech, Glade Spring, VA 24340, USA
[c] School of Animal Sciences, Virginia Tech, Blacksburg, VA, USA 24061

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ABSTRACT

Significant genetic variability exits within sheep breeds for gastrointestinal nematode (GIN) resistance. Therefore, selection may be an important tool to combat anthelmintic resistance in GIN populations. To better understand the effect of selection based on the fecal egg count (FEC) estimated breeding value (EBV) on lamb GIN resistance in a pasture-based system, a divergent mating scheme was established. Over two years, Katahdin rams with exceptionally high (High FEC; n = 5) or low (Low FEC, n = 5) FEC EBV were mated to random groups of Katahdin ewes at the Southwest Virginia Agricultural Research and Extension Center (Glade Spring, VA). Lambs were born mid-March and managed as one contemporary group (Weaning: June 4). In Year 1 (YR1), FEC was collected on all lambs June 26 with no prior anthelmintic treatment. In Year 2 (YR2), beginning at 60 days of age, body weights and FAMACHA scores were collected weekly and FEC biweekly. Anthelmintic administration occurred based on FAMACHA ≥ 3 in YR2. Lamb survival determination excluded first 7 days of age. Statistical analysis was performed using SAS (SAS Institute, Cary, NC) with fixed effects of sire type. Lamb FEC EBV corresponded to sire type validating the mating scheme. Lamb FEC was similar and variable prior to and shortly after weaning. After this point, High FEC-sired lambs had greater FEC compared to Low FEC-sired lambs ($P < 0.05$) and anthelmintic treatment corresponded to FEC EBV type ($P < 0.05$). In YR1, death losses were greater for High FEC-sired lambs ($P < 0.05$) and those lambs that died had greater FEC EBV than those that survived ($P < 0.05$). In YR2, post-weaning FEC EBV difference between High FEC-sired lambs that survived to 120 days of age and those that died was significant (73% vs. 138%, $P < 0.01$). Therefore, selection for improved GIN resistance using FEC EBV is effective and the FEC EBV is also associated with lamb survival in a pasture-based system.

1. Introduction

Gastrointestinal nematodes (GIN) are a major challenge to sheep production globally. These GIN infections result in reduced performance and significant economic losses (Sackett et al., 2006; Mavrot et al., 2015). Further production challenges result from anthelmintic resistance in worm populations (Howell et al., 2009). Therefore, an integrated approach to parasite management may be a more sustainable solution. The combination of nutritional management (Mata-Padrino et al., 2019), selective deworming (Kaplan et al., 2004), anthelmintic alternatives (Burke and Miller, 2006; Burke et al., 2016) and genetic selection could help mitigate anthelminthic needs.

There is significant variability in genetic resistance to internal parasitism. This variability exists within and among breeds (Notter et al., 2003; Vanimisetti et al., 2004b; Notter et al., 2007). Fecal egg count (FEC) is a reliable indicator of parasitism with moderate heritability (Vanimisetti et al., 2004a; Ngere et al., 2018). Estimated breeding values (EBV) for FEC have been available through the National Sheep Improvement Program (NSIP) since 2003 (Notter et al., 2007). The FEC EBV is expressed as a percentage change in FEC. Negative FEC EBV indicates the genetic merit to reduce FEC (Notter and Lewis, 2018). Selection for reduced FEC in Australian Merinos has resulted in improved parasite resistance in progeny and lower periparturient rise (PPR) in ewes (Woolaston et al., 1990; Woolaston, 1992). This is an example of successful selection for disease resistance.

Selection for disease resistance can be challenging due to the cost

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* Correspondence to: 1194 Evansdale Dr., 2213 Ag Science Building, Morgantown, WV 26506, USA.
E-mail address: scott.bowdridge@mail.wvu.edu (S.A. Bowdridge).

[1] Current Address: Department of Animal Science, North Carolina State University, Raleigh, NC 27695 USA.

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associated with identification and measurement of indicator traits (Snowder, 2006). If genes controlling disease resistance are not mutually exclusive, then selection for resistance to one disease could improve resistance to other diseases, resulting in improved general immunity. In a quantitative form, this is expressed as co-heritability ($r_gh_1h_2$) where r_g is the genetic correlation between traits and h_1 and h_2 are the square roots of the heritability for disease traits. When comparing economically relevant diseases in the Merino, positive coheritability existed for parasite resistance compared to foot rot and dermatophilosis (Raadsma et al., 1997). However, beyond this Merino flock, little evidence exits of general immunity and correlative responses to selection for disease resistance.

The Katahdin hair sheep was developed by Michael Piel of Maine during the late 1950′s from crosses of “African Hair Sheep” and traditional wool breeds (Breed Origin & History, 2019). These “African Hair Sheep” were imported from the Caribbean island of St. Croix and were likely Virgin Island Whites, a predecessor of the St. Croix breed (Wildeus, 1997). The Katahdin has since become the most registered breed in the U.S. (Morgan, 2019). Known for its hair phenotype and forage-adaptability, the breed has traditionally been considered relatively parasite resistant. However, significant variability exists based on the FEC EBV (NSIP Searchable Database, 2019). Thus, challenges arise in selecting for resistance and management of lambs in forage-based production systems with significant parasite exposure.

Lambs are most susceptible to parasitism during their first exposure. Primary GIN infections are more severe than subsequent challenge infections (Jacobs et al., 2015). In a forage-based system, this exposure occurs when lambs begin grazing. In spring lambing flocks, weaning and associated lamb stress coincides with GIN establishment and the pathologies resulting from the primary GIN infection. Therefore, improved selection of lambs in forage-based production systems to reduce parasitism around the time of weaning could be beneficial.

The aim of this study was to assess the effect of sire FEC EBV on lamb GIN resistance and fitness around the time of weaning in a pasture-based system. The relationship between parasitism and potential susceptibility to other pathogens will be examined using lambs bred to be parasite susceptible or parasite resistant based on FEC EBV. It is hypothesized that young lambs from extreme positive or extreme negative FEC EBV rams will have corresponding FEC. Additionally, disease fitness is expected to be correlated negatively with individual FEC EBV.

2. Materials and methods

2.1. Breeding Scheme

Rams were sourced from industry flocks participating in NSIP to provide connectedness between Katahdin flocks. Registered Katahdin sires were selected based on post-weaning FEC EBV. With the exception of one sire (High Sire 5 in Year 2 (YR2)), only proven rams were utilized and EBV accuracy for FEC traits was over 0.70. The USA Maternal Hair Index values (based on maternal weaning weight, weaning weight, number of lambs born and weaned EBVs; Notter and Lewis, 2018) were used to ensure sires were relatively similar in genetic merit beyond the FEC EBV. In general, index values varied from 103.9 to 106.3. High Sire 5 had an index score of 112.5 but was needed for equal representation of sire EBV types. In Year 1 (YR1), a total of 4 sires were used with exceptionally high (High FEC) or exceptionally low (Low FEC) FEC EBV (Table 1). In YR2, 8 sires were used. High Sire 1 and Low Sire 1 from YR1 were utilized again in YR2 for connectedness. Average difference in post-weaning FEC (PFEC) EBV between sire groups in YR1 was 300.9% and in YR2, PFEC difference was 421.0%.

Rams were mated to the ewe flock at the Southwest Virginia Agricultural Research and Extension Center (SWAREC, Glade Spring, VA). Registered Katahdin ewes (YR1, n = 119; YR2, n = 137) were randomly assigned to service sire mating groups with even distribution of ewe age (Table 1). Ewe age ranged from lamb (approximately 7 months) to 9 years of age. Half-sibling matings were avoided. Ewe PFEC EBV was similar between Low FEC and High FEC mating groups (YR1: −34 vs. −39%; YR2: −21 vs. −34%; respectively). Inbreeding in resulting progeny was negligible (< 3%). Ewes were exposed to rams for natural mating beginning October 15 in each year. Sires were removed from breeding groups after approximately 45 days. In YR1, 97 ewes lambed. In YR2, 104 ewes lambed (Table 2).

2.2. Management

Timeline for lamb management and data collection is outlined in Fig. 1. Lambs were born at the SWAREC from March 9 to April 29 in YR1 with an average lambing date of March 19 (Table 2). In YR2, lambing date ranged from March 13 to April 13 with an average lambing date of March 24 (Table 2). Lambs were jugged at birth and returned to pasture with their dam after 24–48 h. Lambs were managed on fescue-based mix forage pasture until weaning at approximately 70 days of age. The flock was managed as one contemporary group and rotated among paddocks

Table 1
Sire summary for Year 1 (YR1) and Year 2 (YR2) matings with estimated breeding values (EBV).

					EBV[a]		
Sire ID[b]	YR1 Ewes[c]	YR2 Ewes[c]	WWT (kg)	PWWT (kg)	WFEC (%)	PFEC (%)	USA Hair
Low Sire 1	30	17	3.6	6.0	-20.6	-67.8	104.5
Low Sire 2	30	-	2.1	3.1	-37.4	-81.5	106.1
Low Sire 3	-	18	2.4	4.6	-90.8	-99.5	106.3
Low Sire 4	-	17	0.1	-1.1	-99.4	-99.1	104.2
Low Sire 5	-	17	1.0	2.0	-11.0	-78.7	103.9
Low FEC Average	**60**	**69**	**1.8**	**2.9**	**-51.8**	**-85.3**	**105.0**
High Sire 1	29	17	0.4	1.3	288.5	348.8	105.1
High Sire 2	30	-	1.8	3.7	47.0	103.5	105.8
High Sire 3	-	17	2.5	3.6	135.9	509.7	105.1
High Sire 4	-	17	1.8	2.4	22.0	120.4	105.1
High Sire 5	-	17	0.9	1.7	205.0	359.8	112.5
High FEC Average	**59**	**68**	**1.5**	**2.5**	**139.7**	**288.4**	**106.7**
Sum/Difference[d]	**119**	**137**	**0.4**	**0.4**	**191.5**	**373.8**	**1.7**

[a] Estimated breeding values based on 6/15/2019 Lambplan analysis; weaning weight (WWT), post- weaning weight (PWWT), weaning fecal egg count (WFEC), post-weaning fecal egg count (PFEC), and USA Hair index.

[b] Sire ID denotes grouping based on FEC EBV. Two sires in each group were utilized for breedings in YR1. Three new sires along with a carryover sire were used in YR2.

[c] Represents number of ewes mated to each sire in each year.

[d] Sum of ewe numbers. Difference in low and high FEC sire EBV.

Table 2
Lambing summary.

Sire ID[a]	Ewes[2]	Lambing Date[3]	NLB[b]	NLW[c]
Yearl	22	3/20/2018	1.8	1.7
Low Sire **1**				
Low Sire 2	25	3/17/2018	1.8	1.5
LowFECMean	**47**	**3/18/2018**	**1.8**	**1.6**
High Sire **1**	25	3/20/2018	2.3	1.4
High Sire 2	25	3/20/2018	1.8	1.7
High FEC Mean	**50**	**3/20/2018**	**2.0**	**1.5**
Sum/Mean[d]	**97**	**3/19/2018**	**1.9**	**1.6**
Year2	13	3/20/2019	2.2	1.8
Low Sire **1**				
Low Sire 3	12	3/24/2019	2.1	1.8
Low Sire 4	14	3/23/2019	2.2	1.9
Low Sire 5	11	3/21/2019	2.2	1.8
Low FEC Mean	**50**	**3/22/2019**	**2.2**	**1.8**
High Sire **1**	15	3/27/2019	1.9	1.7
High Sire 3	14	3/22/2019	1.7	1.4
High Sire 4	12	4/6/2019	1.9	1.8
High Sire 5	13	3/23/2019	2.1	1.6
High FEC Mean	**54**	**3/27/2019**	**1.9**	**1.6**
Sum/Mean[d]	**104**	**3/24/2019**	**2.0**	**1.7**

[a] Sire ID denotes grouping based on FEC EBY. [2]Represents number of ewes lambing to each sire. [3]Mean lambing date for ewes mated to each sire.

[b] Mean number of lambs born (NLB) per ewe lambing sired by each ram [5]Mean number of lambs weaned (NLW) per ewe lambing sired by each ram. [6]Sum of ewe numbers, mean lambing date and NLB or NLW.

[c] Mean number of lambs weaned (NLW) per ewe lambing sired by each ram.

[d] Sum of ewe numbers, mean lambing date and NLB or NLW

based on forage availability. Ewes were supplemented with a concentrate pellet (13% CP, 75% TDN). Lambs shared feed with their dams but did not have access to a separate creep area. Lamb deaths were recorded, and cause of death identified if possible by the attending veterinarian. Necropsies were performed when possible and samples analyzed at a state diagnostic laboratory. At weaning (June 4 in each year), lambs were moved to a clean (ungrazed) pasture and managed for an additional 30–45 days. In YR1, lambs were vaccinated for *C. perfringens* types C and D as well as *C. tetani* (Bar Vac® CD/T) at approximately 45 days of age and a booster given the day of weaning. In YR2, lambs were vaccinated at approximately 60 days of age and the booster was given one week after weaning. Additionally, lambs were vaccinated for *C. perfringens* type A (Elanco) in YR2. After weaning, lambs were supplemented 2% body weight with a concentrate pellet (13% CP, 75% TDN).

2.3. Data collection

In YR1, lambs were removed from pasture 22 days after weaning (June 26). A fecal sample was collected rectally, and all lambs were dewormed with levamisole hydrochloride (8 mg/kg, Agrilabs, Columbia, MO, USA). Body weights were taken at weaning and used to calculate adjusted weaning weights. Weaning weights were adjusted for lamb and ewe age, sex, and birth/rear type based on Katahdin adjustment factors. June 26 FEC was considered the weaning FEC (WFEC).

Following YR1, a greater understanding of lamb parasitism and death losses in the time period around weaning was needed. To address this, in YR2, sample collection began at the time of first vaccination (45–60 days of age). Body weights and FAMACHA scores were collected weekly until July 9 (approximately 110 days of age). Fecal samples were collected biweekly. At this point, lambs were removed from pasture and treated with levamisole hydrochloride (8 mg/kg, Agrilabs, Columbia, MO, USA). May 28 FEC was considered WFEC. June 4 weaning weight was used for adjusted weaning weight calculation. Foot scald was assessed weekly by visual evaluation of lameness by research station staff and treated with gamithromycin (6 mg/kg, Merial) if any lameness associated with tissue necrosis between or on hooves was observed. Lambs were given anthelmintic treatment (levamisole hydrochloride) based on FAMACHA™ score ≥ 3 at the time of sample collection which is standard practice at the SWAREC. After a lamb was given anthelmintic treatment, subsequent FEC data were removed from analysis.

A modified McMaster test (Whitlock, 1948) was used to measure FEC. Raw egg counts were multiplied by 50 to determine FEC in eggs/g. Lamb death was recorded from birth to removal from pasture for survival evaluation. For analysis, only lamb death after 7 days of age was considered.

2.4. Statistical analysis

Data were analyzed using SAS (SAS Institute, Cary, NC). Following anthelmintic treatment, FEC data were removed from further analysis to prevent bias in sire types (High FEC, Low FEC) treated more frequently. A log transformation was used on FEC data [ln(FEC+1)] for normality. The Mixed Model procedure of SAS with fixed effects of sire type and random effects of individual sire were used for body weight, FAMACHA score, FEC and EBV data. In YR2, time and sire type X time interaction were included in a repeated measures model for FEC data. Lamb birth and weaning data (body weight and FEC) were processed by Lambplan (Sheep Genetics, Australia) for EBV generation. Lamb FEC EBV was compared by lamb survival status within sire type. Bonferroni's adjustment was used for separation of least-squares means. Significance was determined at $P \leq 0.05$. Tendencies were determined at $0.05 < P \leq 0.10$.

The Genmod procedure was used for deworming frequency, foot treatment and lamb death data with fixed effects of sire type. Deworming frequency and foot treatment data were analyzed as the cumulative total of lambs treated by sire type over the sampling period.

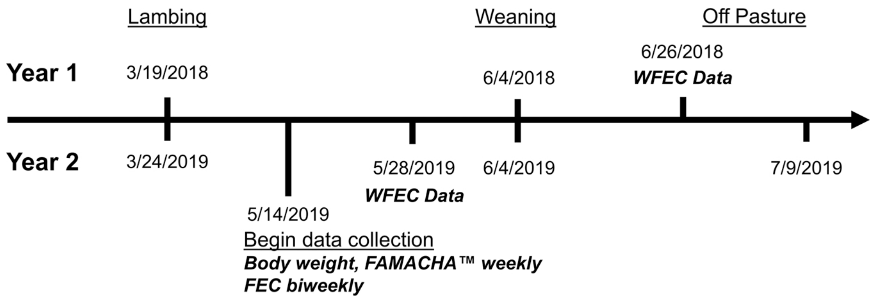

Fig. 1. : Timeline of lamb management by year. Average lambing, weaning and off-pasture dates for each year. In Year 1, weaning fecal egg count (WFEC) data was collected for NSIP data submission on 6/26/2018. In Year 2, body weights and FAMACHA™ scores were collected weekly and FEC biweekly from 5/14/2019 until removal from pasture. WFEC data were collected one week prior to weaning.

3. Results

3.1. Weaning performance

Average lambing date and litter size were similar between sire types (Table 2). In YR2, lambs sired by High Sire 4 were approximately two weeks younger than the rest of the lamb crop. At weaning, differences in adjusted weaning weights were similar to those expected based on WWT EBV (Table 3). Lamb FEC EBV validated the selection scheme (Table 3). For phenotypic comparison of FEC between years, in YR2, June 25 FEC was used. Trends in weaning FEC followed those expected by WFEC EBV (Table 3), although the magnitude of FEC differences was less than that predicted by EBV.

Prior to weaning, FEC was similar between sire types. After weaning, FEC was variable for approximately 3 weeks and FEC differences between sire types did not follow expected trends based on FEC EBV. After this period, FEC segregated as expected with higher FEC in lambs sired by High FEC sires compared to lambs sired by Low FEC sires ($P < 0.05$, Fig. 2A). Comparing sire types, FEC in lambs sired by Low FEC sires (Fig. 2B) peaked shortly after weaning and then generally declined until the end of the sampling period. In almost all lambs sired by High FEC sires, FEC remained constant or continued to rise after weaning (Fig. 2C).

Anthelmintic treatment frequency was similar between sire types prior to weaning. After weaning, anthelmintic treatment differences segregated. A greater percentage of lambs sired by High FEC sires required treatment after weaning and differences remained consistent through the end of the sampling period ($P < 0.05$, Fig. 2D). At the end of the sampling period, the cumulative proportion of lambs treated with anthelmintic was 15% greater in the High FEC-sire group compared to the Low FEC-sire group (Fig. 3D). Individual sire differences were variable and ranged from 39% of lambs sired by Low Sire 3–89% of lambs sired by High Sire 3 (Fig. 3G).

3.2. Survivability

Significant death losses occurred in YR1 with few clinical symptoms prior to death. Veterinary diagnosis confirmed by a state diagnostic laboratory determined cause of death to be *C. perfringens* type A. Lambs sired by High FEC sires had greater death losses than lambs sired by Low FEC sires (29.9% vs 10.6%, respectively; $P < 0.05$, Fig. 3A). Due to a general tendency of lamb loss prior to 7 days of age, unrelated to sire selection, these data were excluded from survivability analysis. In YR1, FEC data were not collected until late June so it is unclear if lamb losses in spring and early summer were associated with parasitism. However, FAMACHA™ scoring was used by SWAREC staff to monitor anemia levels (unreported) and no concern for parasitism appeared during this time period.

Lamb loss was lower in High FEC-sired lambs in YR2 compared to YR1. However, lamb loss was similar in Low FEC-sired lambs in both years (Fig. 3A). In YR2, lambs were vaccinated for *C. perfringens* type A in addition to *C. perfringens* C and D and *C. tetani*. Vaccination appeared to reduce lamb loss in High FEC-sired lambs. Lamb loss in Low FEC-sired lambs may represent standard losses expected in this management system and environment.

In both years, treatment for foot scald was determined based on lameness assessed weekly. Foot treatments were variable between years and sires and was not consistent with sire type (Fig. 3B-C). In YR1, foot treatments ranged from 16% in High Sire 2–44% in Low Sire 2 (Fig. 3E). In YR2, foot treatments ranged from 38% in Low Sire 5–83% in High Sire 3 (Fig. 3F). Sires with the lowest percentage of lambs treated in both years were raised in close geographic proximity to the research station.

3.3. EBV and survivability comparisons

Lamb EBV were generated based on pedigrees and lamb performance through this weaning period. Fecal egg count EBV was used to compare selection for FEC EBV with parasite resistance and survivability. Weaning FEC and PFEC EBV averages between those of lambs that died in each year and those that survived are shown in Fig. 4A and D. Lambs

Table 3
Lamb performance summary with lamb estimated breeding value (EBY).

			Lamb EBV				
Sire ID[1]	WWT (kg)	PWWT (kg	WFEC (%)	PFEC (%)	USA Hair	Adj. WWT[3] (kg)	FEC[4] (eggs/g
Year 1							
Low Sire 1	2.3	3.8	-8.0	-40.6	103.6	16.6	2443
Low Sire 2	1.6	2.4	-38.7	-68.0	105.0	16.4	1134
Low FEC Average	**2.0**	**3.1**	**-23.4**	**-54.3**	**104.3**	**16.5**	**1821**
High Sire 1	0.7	1.5	90.8	101.7	104.7	15.1	3029
High Sire 2	1.5	2.9	6.6	21.1	104.5	16.2	2825
High FEC Average	**1.1**	**2.2**	**48.7**	**61.4**	**104.6**	**15.7**	**2914**
Difference[5]	**0.9**	**0.9**	**72.1**	**115.7**	**0.3**	**0.8**	**1093**
Year 2							
Low Sire 1	2.3	3.9	-10.2	-41.6	104.7	18.1	2150
Low Sire 3	1.8	3.3	-66.1	-84.6	105.8	18.6	1815
Low Sire 4	0.6	0.5	-81.1	-80.4	103.5	16.4	1313
Low Sire 5	1.1	2.1	-12.5	-58.3	103.4	16.7	3938
Low FEC Average	**1.5**	**2.5**	**-42.5**	**-66.2**	**104.4**	**17.5**	**2175[a]**
High Sire 1	0.8	1.8	107.7	118.3	104.2	16. 1	4064
High Sire 3	1.7	2.6	28.2	114.0	103.9	18.5	1471
High Sire 4	1.6	2.4	-6.6	24.5	105.7	18.3	4517
High Sire 5	0.8	1.5	43.5	71.8	108.3	16.8	2056
High FEC Average	**1.2**	**2.1**	**43.2**	**82.2**	**105.5**	**17.4**	**3398[b]**
Difference[5]	**0.2**	**0.4**	**85.7**	**148.4**	**1.2**	**0.1**	**1223**

Different letters denote significance $P \leq 0.05$ within column.

[1] Sire ID denotes grouping based on FEC EBV. Two sires in each group were utilized for breedings in YR1.

[2] Estimated breeding values based on 6/15/2020 Lambplan analysis; weaning weight (WWT), post-weaning weight (PWWT), weaning fecal egg count (WFEC), post-weaning fecal egg count (PFEC), and USA Hair index.

[3] Weaning weights (WWT) adjusted for lamb and dam age, number of lambs born and weaned and sex.

[4] year I fecal egg count (FEC) based on 6/26/ 18 FEC. Year 2 FEC based on 5/29/ 19 FEC.

[5] Difference in low and high FEC sired lambs EBV and performance metrics.

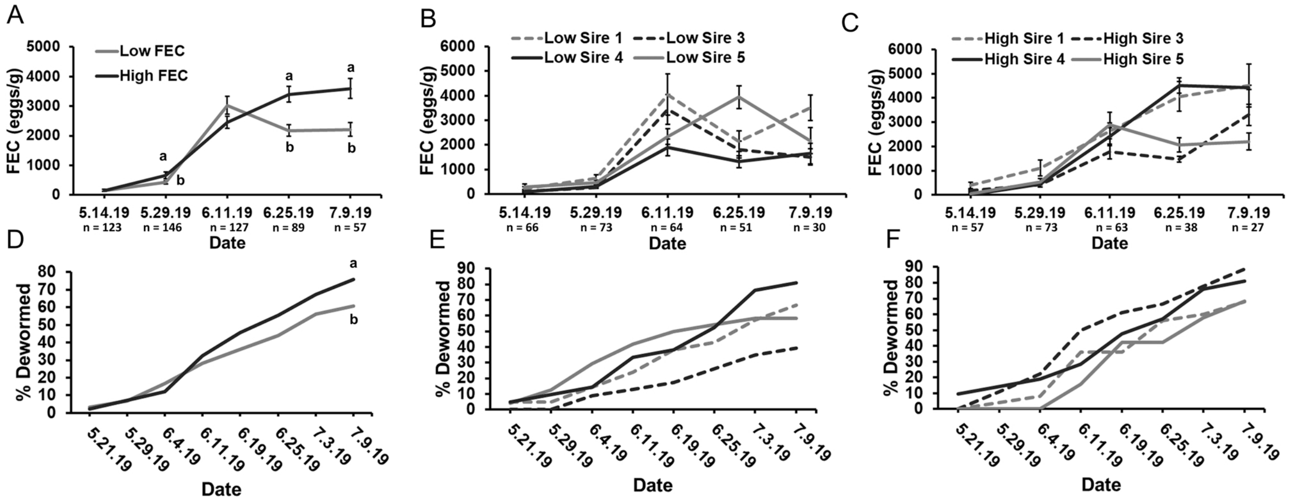

Fig. 2. : Year 2 fecal egg counts (FEC) and anthelmintic treatment. Lamb FEC by sire type (A) beginning at approximately 60 days of age until removal from pasture. Lamb FEC by Low FEC (B) and High FEC (C) sires. Cumulative deworming by sire type (D) over this period. Deworming data by Low FEC (E) and High FEC (F) sires. Once lambs were dewormed, subsequent FEC data were removed from analysis, however the number of lambs contributing to mean FEC data are indicated below date in A-C. Some lambs did not provide a sufficient quantity of fecal material at sampling and were also not included in analysis. Different letters denote significant differences by sire type $P \leq 0.05$.

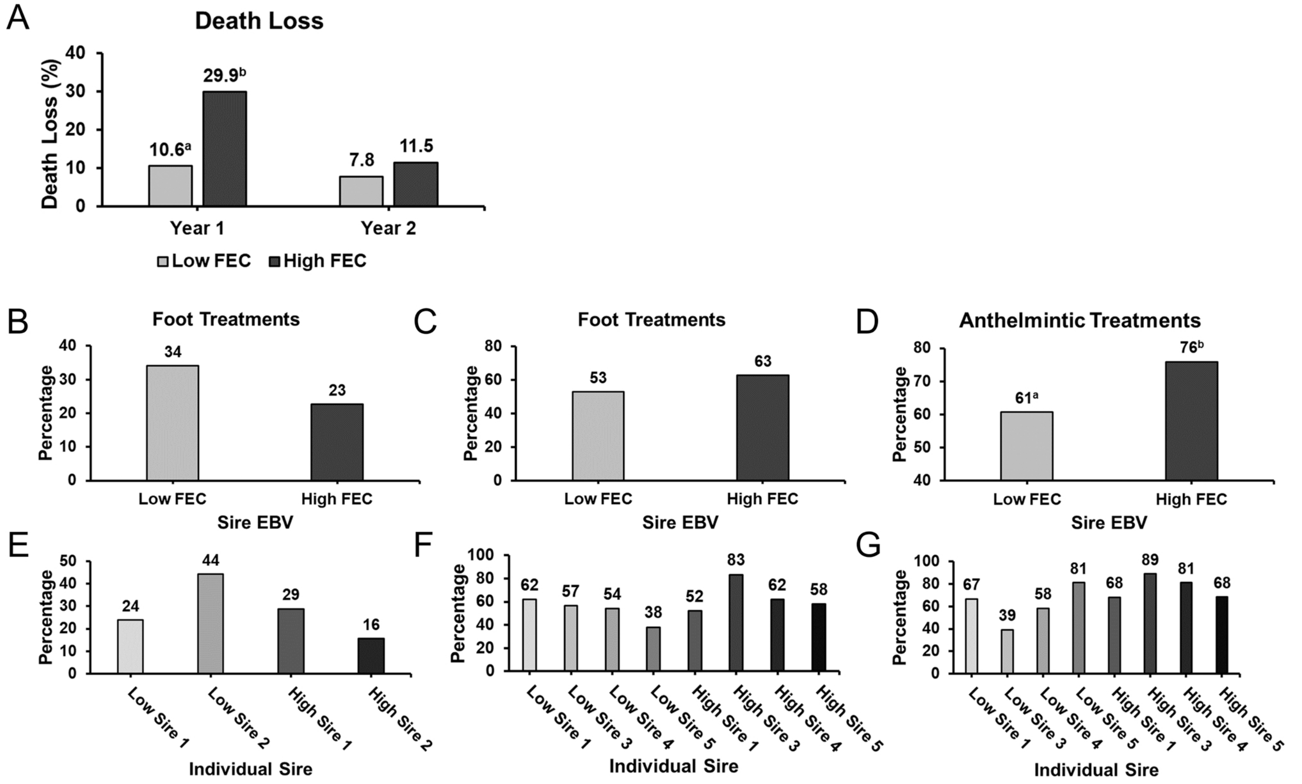

Fig. 3. : Lamb death losses and treatment. Death losses after 7 days of age until removal from pasture (A). Lamb foot treatments by year (Year 1: B,E; Year 2: C,F) for sire type (B-D) and individual sire (E-G). Data represent cumulative treatments for foot scald from birth to removal from pasture. No anthelmintic treatments were given prior to removal from pasture in Year 1. Cumulative anthelmintic treatments in Year 2 from birth to removal from pasture by sire type (D) and individual sire (G). Different letters denote significant $P \leq 0.05$.

that did not survive had greater WFEC and PFEC EBV in YR1 ($P < 0.05$).

Further, survival differences and FEC EBV were compared by sire type (Fig. 4B and C, E and F). In general, the magnitude of FEC EBV difference between the lambs which survived and those lambs which died was greater for High FEC-sired lambs than Low FEC-sired lambs. In YR2, Low FEC-sired lambs that died had a WFEC EBV of − 48.3% compared to − 41.9% for those that survived, a difference of 6.4% (Fig. 4B). In contrast, for High FEC-sired lambs, those lambs that died had a greater WFEC EBV than those that survived (83.1% vs. 36.8%, $P < 0.05$; Fig. 4C). A similar trend existed for PFEC EBV (Fig. 4F) as High FEC-sired lambs that died had a greater PFEC EBV compared to those that survived (137.6% vs. 73.2%, $P < 0.05$). The difference within Low FEC-sired lambs was negligible. Taken together, lamb loss when using Low FEC EBV rams is unpredictable. Losses are environment-dependent

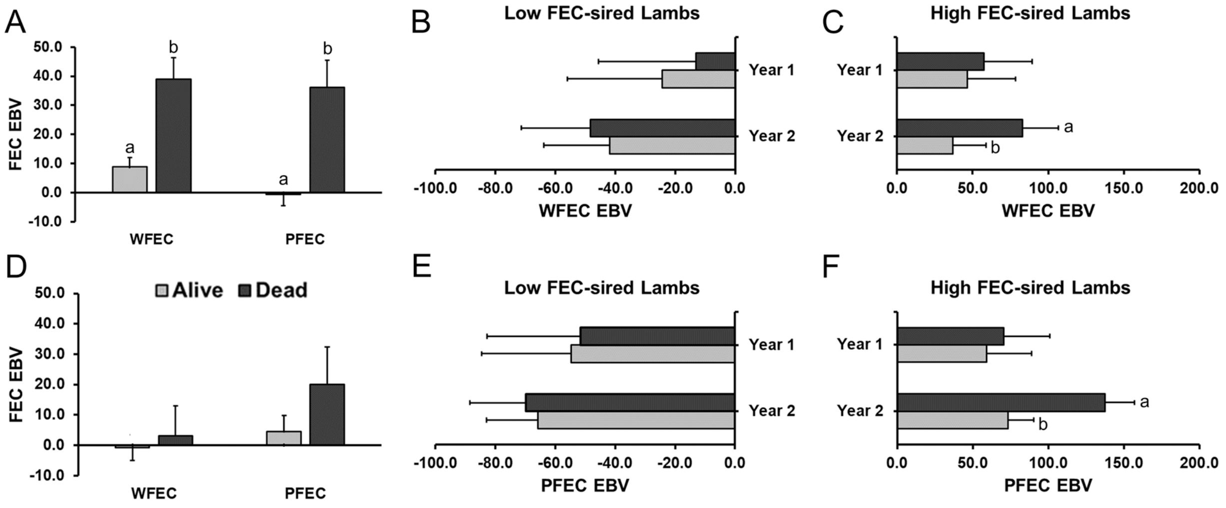

Fig. 4. : Lamb fecal egg count (FEC) estimated breeding value (EBV) and survivability. Weaning fecal egg count (WFEC) estimated breeding value (EBV) and post-weaning FEC (PFEC) EBV for live lambs (Alive) and those lambs that died (Dead) prior to removal from pasture (A and D) in years 1 and 2 respectively. Lamb WFEC EBV (B and C) and PFEC EBV (E and F) by sire type and year for lambs that lived and those that did not. Different letters denote significance $P \leq 0.05$.

and occur regardless of lamb FEC EBV. However, when using High FEC EBV rams, higher death losses may be realized in those lambs with more extreme positive FEC EBV.

4. Discussion

Parasitism is a significant hindrance to lamb production in pasture-based production systems. Lambs are generally more susceptible to infection than mature sheep (Notter et al., 2017). This, in combination with stress associated with weaning, can result in a rise in GIN infection and consequent pathologies such as anemia, hypoproteinemia, and death in severe infections (Zajac, 2006). Additionally, disease challenge in pasture-based systems can result in further losses.

Clostridium perfringens is associated with enterotoxemia or overeating disease (Simpson et al., 2018). *C. perfringens* type C and D are most common; however, increased incidence of type A has been observed in regional proximity to the SWAREC. In YR1, with no vaccination for type A, significant lamb loss was observed from 7 days of age until approximately 100 days of age in High FEC-sired lambs. In YR2, with vaccination for type A, death losses between High and Low FEC-sired lambs were more similar. However, in both years, losses from lambs sired by Low FEC rams were consistently around 10%. Given selection for reduced FEC and improved parasite resistance, death losses of around 10% could be expected for this management system and environment. Death losses above that observed in Low FEC-sired lambs could be a result of compromised immunity and increased susceptibility to parasitism and possibly other pathogens. In Soay sheep populations, increased parasite-specific antigen concentration was associated with improved overwinter survivability (Watson et al., 2016). A similar connection between an adaptive response to the GIN infection and environmental fitness may be present here. Sheep with enhanced parasite resistance may also be better adapted to harsh environmental conditions with a multitude of pathogenic challenges.

The improved survival of High FEC-sired lambs after vaccination for *C. perfringens* type A in YR2 supports *C. perfringens* type A as the possible causative agent resulting in the death losses observed in YR1. These data indicate that High FEC-sired lambs were unable to respond to the pathogen in the absence of vaccination. Regardless, death losses were greater than Low FEC-sired lambs in YR2. Additionally, lambs that died had greater FEC EBV; thus within sire type, greater death losses may be observed in High FEC-sired lambs with more extreme FEC EBV.

Raadsma et al. (1997) suggested that resistance to parasitism may be weakly correlated with foot rot and dermatophilosis resistance. In Fig. 3, incidence of foot scald was variable between years and sires. Thus, consistent relationship with sire type and FEC EBV was lacking.

The divergent mating scheme validated EBV use as a selection tool and potential predictor of lamb GIN resistance. Differences in adjusted weaning weight between sires were small yet comparable to that predicted by WWT EBV. Trends in FEC differences were as predicted by WFEC and PFEC EBV. Removal of FEC data after anthelmintic treatment in YR2 may have reduced mean FEC of High FEC-sired lambs resulting in a lower magnitude of FEC difference between High and Low FEC-sired lambs compared to EBV estimates. Selection for reduced FEC has been successful in Merino populations (Woolaston et al., 1990). Additionally, this selection resulted in a reduction in the periparturient rise (PPR) in FEC indicating that similar genes control both lamb parasitism and ewe PPR (Woolaston, 1992; Notter et al., 2018). Genetic relationships between FEC and body weight appear to be small and relatively unrelated (Ngere et al., 2018). Therefore, simultaneous selection for growth and parasite resistance should not be antagonistic.

Fecal egg count variation around the time of weaning should be considered when collecting samples for genetic analysis. The NSIP database reports WFEC (45–90 days of age) and PFEC (91–150 days of age). The variation in FEC and deviation from expected trends in the time period up to 3 weeks post-weaning could result in inaccurate WFEC EBV if data are submitted from samples collected in this time period. Rather, WFEC should be collected shortly before or on the day of weaning. If unable, sample collection should wait until at least 3–4 weeks post-weaning.

In conclusion, the FEC EBV is a reliable predictor of lamb FEC and resistance to parasitism. Data collection for generation of FEC EBV should be restricted from the period beginning at weaning to 3–4 weeks post-weaning to limit FEC inaccuracy from environmental stress. The FEC EBV may also be associated with lamb survival. Greater lamb mortality was observed in High FEC-sired lambs and lambs with greater individual FEC EBV. The FEC EBV could be a potential predictor of lamb survival in pasture-based production systems. Possible implications of selection for FEC EBV could be improved lamb fitness and survival despite a variety of pathogenic challenges.

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Declaration of Competing Interest

The authors of the manuscript titled “Effect of sire fecal egg count estimated breeding value on Katahdin lamb pasture performance” declare no competing financial conflict of interest with the work being conducted in this manuscript.

References

Breed Origin & History. 2019. Katahdin Hair Sheep Int. Available from: https://www.katahdins.org/about-the-breed/history/.

Burke, J.M., Miller, J.E., 2006. Evaluation of multiple low doses of copper oxide wire particles compared with levamisole for control of Haemonchus contortus in lambs. Vet. Parasitol. 139, 145–149. https://doi.org/10.1016/j.vetpar.2006.02.030.

Burke, J.M., Miller, J.E., Terrill, T.H., Smyth, E., Acharya, M., 2016. Examination of commercially available copper oxide wire particles in combination with albendazole for control of gastrointestinal nematodes in lambs. Vet. Parasitol. 215, 1–4. https://doi.org/10.1016/j.vetpar.2015.11.002.

Howell, S., Burke, J., Miller, J., Terrill, T., Valencia, E., Williams, M., Williamson, L., Zajac, A., Kaplan, R., 2009. Prevalence of anthelmintic resistance on sheep and goat farms in the southeastern United States. . J. Am. Vet. Med. Assoc. 233, 1913–1919. https://doi.org/10.2460/javma.233.12.1913.

Jacobs, J.R., Greiner, S.P., Bowdridge, S.A., 2015. Serum interleukin-4 (IL-4) production is associated with lower fecal egg count in parasite-resistant sheep. Vet. Parasitol. 211, 102–105. https://doi.org/10.1016/j.vetpar.2015.04.024.

Kaplan, R.M., Burke, J.M., Terrill, T.H., Miller, J.E., Getz, W.R., Mobini, S., Valencia, E., Williams, M.J., Williamson, L.H., Larsen, M., Vatta, A.F., 2004. Validation of the FAMACHA© eye color chart for detecting clinical anemia in sheep and goats on farms in the southern United States. Vet. Parasitol. 123, 105–120. https://doi.org/10.1016/j.vetpar.2004.06.005.

Mata-Padrino, D.J., Belesky, D.P., Crawford, C.D., Walsh, B., MacAdam, J.W., Bowdridge, S.A., 2019. Effects of grazing birdsfoot trefoil-enriched pasture on managing Haemonchus contortus infection in Suffolk crossbred lambs. J. Anim. Sci. 97, 172–183. https://doi.org/10.1093/jas/sky405.

Mavrot, F., Hertzberg, H., Torgerson, P., 2015. Effect of gastro-intestinal nematode infection on sheep performance: a systematic review and meta-analysis, 557–557 Parasit. Vectors 8. https://doi.org/10.1186/s13071-015-1164-z.

Morgan, J.L.M., 2019. 2018 KHSI statistics: comparing with other breeds. Katahdin Hairald 31, 3.

Ngere, L., Burke, J.M., Morgan, J.L.M., Miller, J.E., Notter, D.R., 2018. Genetic parameters for fecal egg counts and their relationship with body weights in Katahdin lambs. . J. Anim. Sci. 96, 1590–1599. https://doi.org/10.1093/jas/sky064.

Notter, D.R., Andrew, S.A., Zajac, A.M., 2003. Responses of hair and wool sheep to a single fixed dose of infective larvae of Haemonchus contortus. Small Rumin. Res. 47, 221–225. https://doi.org/10.1016/S0921-4488(02)00279-1.

Notter, D.R., Burke, J.M., Miller, J.E., Morgan, J.L.M., 2017. Factors affecting fecal egg counts in periparturient Katahdin ewes and their lambs1,2,3. . J. Anim. Sci. 95, 103–112. https://doi.org/10.2527/jas.2016.0955.

Notter, D.R., and R.M. Lewis. 2018. NSIP EBV Notebook. Available from: http://nsip.org/wp-content/uploads/2019/01/NSIP-EBV-Descriptions-Update-16-Dec-2018.pdf.

Notter, D.R., Morgan, J.L.M., Vanimisetti, H.B., 2007. Historic EPD for parasite resistance developed for Katahdins. Katahdin Hairald 19, 3–6.

Notter, D.R., Ngere, L., Burke, J.M., Miller, J.E., Morgan, J.L.M., 2018. Genetic parameters for ewe reproductive performance and peri-parturient fecal egg counts and their genetic relationships with lamb body weights and fecal egg counts in Katahdin sheep. . J. Anim. Sci. 96, 1579–1589. https://doi.org/10.1093/jas/sky100.

NSIP Searchable Database. 2019. Natl. Sheep Improv. Program. Available from: http://nsipsearch.nsip.org/#!/search.

Raadsma, H.W., Nicholas, F.W., Egerton, J.R., 1997. Ultimate disease resistance in sheep: What are the relationships between all major diseases? Proc. Assoc. Advmt Breed. Genet 12, 63–67.

Sackett, D., P.H. Holmes, K. Abbott, S. Jephcott, M. Barber. 2006. Assessing the economic cost of endemic disease on the profitability of Australian beef cattle and sheep producers. Meat & Livestock Australia Limited. ISBN: 1741910021.

Simpson, K.M., Callan, R.J., Van Metre, D.C., 2018. Clostridial abomasitis and enteritis in ruminants. Dig. Disord. Abomasum Intest. 34, 155–184. https://doi.org/10.1016/j.cvfa.2017.10.010.

Snowder, G.D., 2006. Genetic selection for disease resistance: challenges and opportunities. BIF Proc. 52–60.

Vanimisetti, H.B., Andrew, S.L., Zajac, A.M., Notter, D.R., 2004a. Inheritance of fecal egg count and packed cell volume and their relationship with production traits in sheep infected with Haemonchus contortus1. . J. Anim. Sci. 82, 1602–1611. https://doi.org/10.2527/2004.8261602x.

Vanimisetti, H.B., Greiner, S.P., Zajac, A.M., Notter, D.R., 2004b. Performance of hair sheep composite breeds: resistance of lambs to Haemonchus contortus1. . J. Anim. Sci. 82, 595–604. https://doi.org/10.2527/2004.822595x.

Watson, R.L., McNeilly, T.N., Watt, K.A., Pemberton, J.M., Pilkington, J.G., Waterfall, M., Hopper, P.R.T., Cooney, D., Zamoyska, R., Nussey, D.H., 2016. Cellular and humoral immunity in a wild mammal: Variation with age & sex and association with overwinter survival. Ecol. Evol. 6, 8695–8705. https://doi.org/10.1002/ece3.2584.

Whitlock, H.V., 1948. Some modifications of the McMaster helminth egg-counting technique and apparatus. J. Counc. Sci. Ind. Res. Aust. 21, 177–180.

Wildeus, S., 1997. Hair sheep genetic resources and their contribution to diversified small ruminant production in the United States. . J. Anim. Sci. 75, 630–640. https://doi.org/10.2527/1997.753630x.

Woolaston, R.R., 1992. Selection of Merino sheep for increased and decreased resistance to Haemonchus contortus: peri-parturient effects on faecal egg counts. Int. J. Parasitol. 22, 947–953. https://doi.org/10.1016/0020-7519(92)90052-M.

Woolaston, R.R., Barger, I.A., Piper, L.R., 1990. Response to helminth infection of sheep selected for resistance to Haemonchus contortus. . Int. J. Parasitol. 20, 1015–1018. https://doi.org/10.1016/0020-7519(90)90043-M.

Zajac, A.M., 2006. Gastrointestinal nematodes of small ruminants: life cycle, anthelmintics, and diagnosis. . Rumin. Parasitol. 22, 529–541. https://doi.org/10.1016/j.cvfa.2006.07.006.