Evaluation of terminal sire breeds for hair sheep production systems

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ACADEMIC ABSTRACT

Terminal sire crossbreeding systems which improve growth performance while maintaining parasite resistance have the potential to enhance the profitability of hair sheep enterprises. Katahdin (KT, n = 4), Suffolk (SU, n = 3), and Texel (TX, n = 3) rams were randomly mated to KT ewes over two years (Y1, Y2) at the Virginia Tech Southwest Agricultural Research and Extension Center. Post-lambing until weaning (80 d), pairs were managed on fescue pasture. At weaning, lambs (n = 192) were moved to an ungrazed pasture and provided a concentrate pellet daily for a 90 d grazing trial. During this time, BW, strongylid egg count (FEC), FAMACHA score and packed cell volume (PCV) were collected every 14 d. FAMACHA score ≥ 3 was utilized as the basis for anthelmintic treatment. Post-grazing, lambs were fed to approximately 50 kg BW. Lambs were harvested at the Virginia Tech Meat Center and carcass evaluation performed 1 d post-harvest. Statistical analyses were conducted using SAS (SAS Institute Inc., Cary, NC) with Proc MIXED for repeated measures analysis and Proc GLM with Tukey's test for mean separation. No differences existed between sire breeds for adjusted number of lambs born or number of lambs weaned. Adjusted birth BW was greater for SU-sired lambs than KT-sired and TX-sired ($P < 0.05$) in Y2. Adjusted weaning BW was smallest for KT-sired lambs compared to SU- and TX-sired lambs ($P < 0.05$) in both years. During the grazing trials, BW, ADG, lnFEC, FAMACHA and PCV varied over time ($P < 0.001$) with lower FAMACHA scores for KT-sired lambs than SU- and TX-sired lambs in Y1 ($P < 0.05$). A greater proportion

of SU-sired lambs tended to require deworming than KT-sired lambs ($P = 0.08$). Adjusted BW post weaning was greater for TX-sired lambs than KT-sired lambs ($P < 0.05$) in Y1. Post-grazing, BW and ADG varied over time ($P < 0.01$) with no sire breed differences for ADG. At harvest, SU-sired lambs were heavier than KT-sired lambs ($P < 0.05$). TX-sired lambs had greater LM area than KT-sired lambs ($P = 0.05$). KT-sired lambs had the smallest leg scores ($P < 0.05$). These results indicate the potential of terminal sires (SU- and TX-sires) to improve lamb growth and carcass merit. TX-sired lambs had more similar parasite resistance characteristics to KT-sired Iambs and may have potential as terminal sires in forage based hair sheep production systems.

GENERAL AUDIENCE ABSTRACT

Katahdin hair sheep have been developed as an easy-care breed adaptable to forage-based production systems. Their enhanced resistance to gastrointestinal parasites has resulted in their rise in popularity among sheep producers in the southeastern United States. However, their lower cutability (muscle to fat ratio) and lighter carcass weights have resulted in economic concerns. Therefore, other breeds (Texel and Suffolk) have been considered for crossbreeding to increase carcass size and muscle improving the market value of lambs produced. Here, Katahdin, Suffolk and Texel sires were mated to Katahdin ewes over two years at the Southwest Virginia Agriculture Research and Extension Center. Lambs were grazed with their dams until weaning at approximately 70 days of age. Post-weaning, lambs were grazed for approximately 90 days during which time body weights and parasite resistance indicators were recorded every two weeks. Lambs were dewormed based on anemia level measured by mucus membrane color (FAMACHA score). After grazing, lambs were fed until they reached approximately 50 kg. Lambs were harvested at the Virginia Tech Meat Center for carcass evaluation. There were no differences between the sire breeds for number of lambs born or weaned per ewe. Suffolk-sired lambs were heaviest at birth in year 2 and at weaning Suffolk- and Texel-sired lambs were heavier than Katahdin-sired in both years. In year 1, Texel-sired lambs were heaviest at the end of the grazing period. FAMACHA scores tended to be lower for Katahdin-sired lambs and Suffolk-sired lambs tended to require greater deworming. At harvest, Suffolk-sired lambs were heavier than Katahdin-sired lambs while the Texel-sired lambs had greater loin muscle area. These results indicate the potential of terminal-sires (Suffolk and Texel) to improve lamb growth. Texel-sired lambs were more similar to Katahdin-sired lambs for resistance traits while

increasing carcass muscling and may be a potential terminal option for forage-based production systems.

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Breed origin, purpose and environment

Introduction

This review will address the origins of the Katahdin (KT), Texel (TX) and Suffolk (SU) breeds and their respective roles in the United States (U.S.) sheep industry. Further discussion will focus on the differences between the breeds for resistance to gastrointestinal nematodes (GIN) and their ability to perform in pasture-based systems in the southeastern U.S. Finally, this review will focus on the variability in carcass merit among the breeds and the resulting differences in-end product value. These points will outline breed characteristics and examine possible terminal-sire options for hair sheep producers.

The Katahdin

The KT breed is a composite between British breeds and those from the Virgin Islands ("African Hair Sheep"). British breeds which were utilized included the SU and the Wiltshire horn. As the breed was developed, selection pressure was placed on the presence of hair coats, a polled phenotype, conformation, prolificacy and growth. Mature sizes range from 68-90 kg for rams and 55-73 kg for ewes and most individuals are white, brown or a combination (Wildeus, 1997). Evidence suggests a greater natural resistance to GIN (lower fecal egg count (FEC) and higher packed cell volume (PCV)) compared to Dorper and Dorset crossbreds (Vanimisetti et al., 2004). Consequently, the KT breed has been heavily utilized by sheep producers in the southern U.S. due to their adaptability to extensive, forage-based environments.

The Texel

Introduction of the TX breed to North America occurred in 1985. Four rams and 20 ewes were imported from Finland along with an additional five rams from Denmark. Individuals were selected based on growth rate and diversity of genetics (Leymaster and Jenkins, 1993). In previous European studies, this breed excelled in lean tissue growth and consequently cutability compared to other sire breeds (Cameron and Drury, 1985**;** Croston et al., 1987; Kempster et al., 1987; More O'Ferrall and Timon, 1977a,b**;** Wolf et al., 1980). Because of these traits, the TX has been evaluated for its potential use as a terminal sire in the U.S. Further European research on parasite resistance traits has shown the TX superior to the SU due to reductions in FEC (Good et al., 2005). Since introduction to the U.S., research has focused on these attributes and their suitability to different production systems in North America.

The Suffolk

The SU breed originated from a cross of the Southdown and Norfolk Horned breeds and has been selected for growth characteristics. Developed in England, this black-faced breed has a large mature size and has been heavily utilized as a terminal sire on white-faced ewe breeds. The SU was brought into the U.S. in 1888. The SU breed, along with breeds such as the Hampshire, Shropshire and Oxford, have been traditional sire breeds in the U.S. (ASI, 2002).

This review will further discuss these breed attributes with respect to traits concerning sheep production in the southeastern U.S. and the potential of the SU and TX breeds as terminal sires in KT-based ewe flocks.

Southeastern United States Climate

In the U.S., there is large variation in climate and consequently, management systems. Sheep production in the southeastern U.S. is influenced by a warm and humid climate. Average annual precipitation ranges from 100 to 200 cm in the region south and east of the Ohio River and Texas border. In this same region, temperatures average 10 to 21° C. These conditions compare to areas north and west of the Ohio River with average temperatures between 4 and 10° C and precipitation from 100 cm to as low as 13-25 cm in the high plains and west (PRISM Climate Group, 2015a,b). These conditions in the southeast provide an excellent climate for forage growth (NOAA, 2016). However, these climate characteristics also provide an ideal environment for the proliferation of GIN, specifically *Haemonchus contortus*. For these reasons, sheep producers must utilize genetics and management strategies to minimize the impact of *H. contortus* on the profitability of their livestock enterprise.

Southeastern United States Sheep Markets

The non-traditional or ethnic market is predominant in the eastern U.S. This market includes those sheep not slaughtered and sold under federal inspection. Despite a steady decline in the number of lambs slaughtered under federal inspection, the non-traditional market has remained relatively constant (Shiflett et al., 2010). Consequently, as a proportion of total lambs marketed, the non-traditional market has increased. It is also estimated that 20% of lambs slaughtered under federal inspection are sold into the ethnic market accounting for approximately 500,000 lambs per year (Shiflett et al., 2010). In the East, New Holland Sale Stables (New Holland, PA) markets approximately 2,100 lambs per week (109,200 per year) and has been a popular location for sourcing lambs into the ethnic markets of east coast population centers. In addition to sale facilities and the traditional to non-traditional route of marketing, direct sales account for approximately one million lambs entering the ethnic market annually. This number is difficult to estimate due to the lack of regulation in this sector of the industry. Differences between the estimated U.S. lamb crop and the sales through federal inspection and auctions can provide an approximation. This non-traditional market desires a lamb of moderate size (30 to 50 kg; Shiflett et al., 2010). Lambs are predominately sold on a live basis and quantifying value of carcass composition has been the subject of some debate. Even so, this non-traditional market has been very strong. Sales at the New Holland auction have surpassed those of western markets in 2015 and 2016 on a weight basis for 27-41 kg lambs (USDA-AMS, 2016). With this strong market and despite a decline in the national sheep population, there has also been a rise in sheep numbers in the southeastern U.S. while areas of the west have seen a decline (Shiflett et al., 2010). This is in spite of concerns for GIN.

Parasite biology and breed differences in resistance

Introduction

From an animal health and economic perspective, parasite burdens on livestock are a major concern for producers. Mavrot et al. (2015) found a negative correlation between GIN and production measures in 86% of trials. Those production measures included BW gain, milk production and wool growth. In studies which compared an infected and naïve animal, a negative correlation was found in 84% of studies associated with BW gain, all studies related to milk production and 74% of studies on wool yields (Mavrot et al., 2015). This decrease in performance directly impacts net profitability for producers. In Australia, the economic impact of decreased BW gain, wool yield and management for GIN amounts to millions of dollars each year (Sackett et al., 2006).

In 1996, the NAHMS reported internal parasites as a top health concern and 62.1% of operations reported internal parasites were of moderate to high burden (USDA-APHIS-VS-NAHMS, 1996). In the 2011 report, over 50% of operations treated newly acquired individuals for GIN. Additionally, internal parasites and coccidiosis accounted for 15.5% of the sheep lost in pasture-based systems after predation and 19.7% of pasture based operations that lost lambs had death loss for these reasons. Further, in the East region, 14.2% of the lambs lost after predation were lost due to internal parasites and 18.1% of operations reported losses for this reason (USDA-APHIS-VS-NAHMS, 2012).

Animal health concerns range from anemia to death of severely infected individuals (Whittier et al., 2009). Livestock producers, especially those in warm and wet climates, such as those in the southern and southeastern U.S., must deal with the impacts of GIN infections. Previous solutions such as routine use of anthelmintics have decreased in their efficacy (Howell et al., 2008). Additionally, genetic selection can have a greater effect on reducing FEC than protein supplementation or strategic deworming (Eady et al., 2003).

Anthelmintics are utilized to treat GIN. Classes of anthelmintics include benzimidazoles, macrocyclic lactones and nicotinics, each with a unique mode of action. In the last 30 years, there have been no new classes of anthelmintic except monepantel (Kaplan et al., 2012). Traditional methods of parasite treatment in sheep flocks consist of regular dosing of livestock with an anthelmintic throughout the grazing season (Terrill, 2012). The GIN population develops resistance to the various classes of anthelmintics as a result. Regular treatment of all animals has resulted in accelerated selection for anthelmintic resistance in parasite populations (Kaplan, 2004).

Concerns about *H. contortus* are present across the world, especially in the southern U.S. Economic losses for GIN treatments range from $26 million in Kenya to $103 million in India and up to $400 million in Australia (Sackett et al., 2006). Concerns for *H. contortus* are associated with its prolificacy and their consumption of blood from the host resulting in anemia. This anemia can result in decreased BW gain or BW loss, brittle wool, occasionally “bottle jaw” (i.e., submandibular edema) associated with hypoproteinemia and sometimes death of the host animal (Whittier et al., 2009). This parasite most commonly causes parasitic gastroenteritis (PGE) in young, immunocompromised individuals or those exposed to high levels of infective larvae (L3) in the environmental (Zajac, 2006). Seventeen to 21 days are required following consumption of L3 for the parasite to reach the adult stage (Levine, 1980).

Another GIN of concern, especially in more temperate climates is *Teladorsagia circumcincta* (Zajac, 2006; Gossner et al., 2013). Also residing in the abomasum, this GIN causes alterations to gastric glands (Levine, 1980) resulting in diarrhea and occasionally anemia and death (Zajac, 2006). Concerns for prolificacy are not as great as those with *H. contortus* and the time from infection to maturity (prepatent period) is similar (Soulsby, 1965).

Trichostrongylus species *(T. colubriformis, T. vitrinus, T. axei)* also impact small ruminant production (Good et al., 2005; Zajac, 2006). These species can cause diarrhea and occasionally death (Bowman, 1999). This parasite survives longer as adults than *H. contortus* or *T. circumcinta* (Courtney et al., 1983).

These strongylid parasites infect the host through consumption of infective larvae (L3) present on contaminated pastures. Following consumption, L3 larvae develop to the adult stage and reside in the abomasum or small intestine. Adults produce eggs which are deposited in the fecal matter. Provided favorable conditions, first stage larvae hatch and begin development to the third or infective stage. These infective larvae migrate on to the leaves of forage where they reside until being consumed (Levine, 1980).

While *Nematodirus* species (Good et al., 2005; Matika et al., 2011) have been of some concern in European countries, issues associated with PGE and this parasite have not occurred in the U.S. (Zajac, 2006).

In a 2008 analysis by Howell et al., 26 sheep farms in the southeastern U.S. were examined including one in St. Croix and two in Puerto Rico. Relating to the drug resistance of *H. contortus*, sheep on 88% of farms were considered resistant to benzimidazole, 4% to levamisole, 42% to ivermectin and 12% for moxidectin. When resistant and low resistance flocks were combined, benzimidazole resistance was found on 96% of farms. Levamisole resistance was found on 54% of farms, ivermectin resistance on 65% and moxidectin resistance on 15% farms. Forty two percent of farms were found to have *H.contortus* resistant to all three classes of anthelmintics (Howell et al., 2008). Even with the intense use of anthelmintics, in Malaysia over 25% percent of the sheep per flock are often lost on an annual basis due to drug resistant internal parasites (Waller et al., 2005).

As defined by Hayward et al. (2014), tolerance is the ability of the sheep to maintain its health as the parasite infection increases as opposed to resistance which relates to reducing the number of parasites by preventing establishment or fecundancy of the GIN. Sheep may be more tolerant to infection but not show the same levels of resistance.

A flock of Soay sheep was studied by Hayward et al. (2014) to examine GIN effects on unmanaged sheep. As expected, the BW of sheep decreased with an increase in GIN. Also, sheep that showed a lower decline in BW as their parasite burden increased produced more lambs. However, large variation existed between sheep related to BW and total burden of GIN. As the GIN loads increased, the sheep that lost BW more slowly and produced more lambs may have shown tolerance as they were able to maintain a level of performance during infection (Hayward et al., 2014).

GIN are a major concern for sheep production worldwide. In particular, *H. contortus* has great animal health and consequently economic impacts. With a rise in anthelmintic resistance among GIN populations, alternatives will be necessary to control GIN burden and sustain individual performance. Tolerance and resistance are important factors when considering GIN management. This chapter will further discuss the mechanisms behind GIN resistance and alternatives to anthelmintic use.

Immune Response

The ability of an individual to resist the deleterious effects of GIN infection is dependent upon the type and extent of the immune response which occurs in the period following consumption of infective larvae. This immune response can be characterized in terms of either humoral, cellular or cytokine responses. Humoral responses are defined by IgE (Pfeffer et al., 1996; Prichard et al., 1997; Shaw et al., 1998; Gill et al., 2000; Huntley et al., 2001; Pernthaner et al., 2005a; Pettit et al., 2005), IgA (Stear et al., 1995; Martinez-Valladares et al., 2005; Henderson and Stear, 2006; Pernthaner et al., 2006) and IgG1 (Gill et al., 2000; Pernthaner et al., 2006). The cellular response to GIN infection involves mast cells (Pfeffer et al., 1996; Gill et al., 2000) and eosinophils (Pfeffer et al., 1996; Gill et al., 2000; Stear et al., 2002; Henderson and Stear, 2006). There is a negative relationship between globule leukocytes and eosinophils. This is likely explained by the different niches in which these cells act. Larvae which avoid initial expulsion by globule leukocytes are then acted upon by eosinophils in the tissue (Balic et al., 2006). With a favored Th2 type response (Lacroux et al., 2006), cytokine expression includes IL-4 (Finkelman et al., 2004; Gossner et al., 2013), IL-5 (Gill et al., 2000; Gossner et al., 2013; Pernthaner et al., 2005b) and IL-13 (Finkelman et al., 2004; Gossner et al., 2013; Perthaner et al., 2005b, 2006) in addition to tumor necrosis factor α (Pernthaner et al., 2005b) and IL-6 mRNA cells (Shen et al., 2000). Further, there was expression at the MHC-DRB1 (Schwaiger et al., 1995; Stear et al., 1996) and IFN – γ loci (Coltman et al., 2001; Sayers et al., 2005). Cytokine production by CD4+ T helper cells results in mast cell and eosinophil recruitment, differentiation and proliferation. While the immunological response to nematode infection is characterized by a Th2 response, a Th1 response is also involved. The Th1 response is defined by IFN – γ and is responsible for the suppression of the Th2 response (Else and Finkelman, 1998). This Th2 response is defined by the greater expression of IL-4 and IL-5 in addition to IL-10 (Mulcahy et al., 2004; Riffkin et al., 1996).

Initial IFN-γ expression could be explained by establishment of infective larvae. After initial establishment, there was greater IL-4 expression associated with a Th2 type response. A decrease in parasite numbers after initial establishment is a result (Shakya et al., 2009). After this primary infection, sheep respond more rapidly to subsequent infections. Sheep which have been infected prior show an increase in B cells, CD4+, and γδ-TCR+ T cells in the abomasal tissue two days earlier than during the first infection (Balic et al., 2002).

There is also a relationship between FEC and *Trichostrongylus colubriformis* L3 antibody levels. The genetic correlation between FEC and these antibody levels is -0.56. More specifically, the correlation between FEC and IgG is -0.35 (Douch et al., 1995). Greater antibody levels are expected in more resistant individuals with lower FEC.

The immune response associated with GIN infection is complex and variable. Even so, there is evidence of an initial Th1 response (Shakya et al., 2009) followed by a greater Th2 response and a decline in a Th1 response (Gill et al., 2000; MacKinnon et al., 2015; Gossner et al., 2013). There is variation between breeds and breed types (e.g., hair breeds vs. wool breeds) which will be discussed in greater detail later. The ability of an individual to resist GIN infection is rooted in the immune mechanism by which the individual responds. Traditionally, FEC has been utilized as an indicator of GIN burden and this FEC is moderately related to antibody levels (Douch et al., 1995).

Genetic Response

To further understand the mechanism of resistance, molecular methods can be used to examine the foundation of the genetic component of resistance.

The QTL associated with parasite resistance are not consistent between different breeds. In TX and SU sheep, QTL associated with parasite resistance to *Nematodirus* are located on chromosomes 3 and 14. However, the QTL associated with other *Strongyles* were only on chromosome 3 of the Suffolk sheep (Matika et al., 2011). Relating to *H. contortus* resistance, almost half of the detected QTL were found on chromosomes 5, 7, and 12. On chromosome 12, a region was found consisting of 10 Mbp which was strongly associated with the FEC after both the first and second infections (Sallé et al., 2015).

When resistant-selected lambs and susceptible- selected lambs were compared to naïve lambs, there was an increase in the expression of FCER2, IGHE and CHI3L2. When resistant-selected lambs were compared to both the susceptible-selected and naïve, there was an increase in the expression of ACTG2, IL-13 and COL6A5. In this comparison a number of genes were repressed as well. These include TNFSF10, CXCR1, CSCR3, CCL5, and CCL11. In relation to the resistant vs. naïve lambs, the most related networks were Humoral Immune Response, Inflammatory Response, Protein Synthesis and Hematological System Development and Function. In this first network, Hummoral Immune Response, Inflammatory Response, Protein Synthesis, the IL-13 gene was the primary gene involved (Gossner et al., 2013). In terms of inflammatory response, DUOX1 and NOS2A have been identified as important to the mechanism of parasite resistance. These genes are associated with free radical production and are expressed more frequently in lambs that also showed greater resistance to GIN (Ingham et al., 2008).

Due to the high levels of anthelmintic resistance in parasite populations of sheep, alternatives must be utilized to prevent further economic losses. Kaplan et al. (2012) suggest non-chemical management strategies will be essential to ensuring success for producers in the future. Using genetic technologies could be a potential strategy in the future. However, both the genetic and immunological responses to infection are complex and further evidence is needed to pinpoint the specific mechanisms of resistance.

Heritability

Heritability is the relationship between genetic and phenotypic variation. As the heritability of a trait increases, genetics account for a greater percentage of that trait's phenotype. The ability to breed sheep for resistance to GIN infection is dependent on the heritability of the factors associated with resistance. That is, the genetic component of the mechanisms of resistance. If a genetic component exists, then measurement and selection could be used to breed for individuals with greater resistance. FEC and PCV can be used as indicator traits to measure resistance.

Heritabilities for FEC range from 0.10 to 0.38 in lambs (Assenza et al., 2014; Miller et al., 2006; Vanimisetti et al., 2004). In ewes, the heritability is approximately 0.31 (Vanimisetti et al., 2004). This heritability is variable between first and second infection with greater heritabilities (0.48-0.55) during secondary infection (Assenza et al., 2014). Further, the heritability during artificial infection (0.12) is lower than during natural infection (Miller et al., 2006). In Australian Merinos, the heritability of FEC ranged from 0.29 at weaning to 0.16 at a year of age potentially resulting from differences in environment and GIN exposure at older ages. Genetic correlations between FEC at various ages were high (0.40 to 1.0). In addition, genetic correlations between FEC and BW traits were low (Brown and Fogarty, 2016). Heritabilities for PCV range from 0.12 to 0.39 for lambs (Miller et al., 2006; Vanimisetti et al., 2004) with lower heriabilities (0.12) during artificial infection (Miller et al., 2006). In ewes, the heritability is approximately 0.15 (Vanimisetti et al., 2004).

As expected, PCV is positively correlated with BW and negatively correlated with FEC. Yearling ewes are less resistant to infection than older ewes; however, fertility and prolificacy were not related to parasite resistance. Related to BW and growth, ewes that had higher genetic merit for growth as lambs were less resistant to parasites as adult ewes (Vanimisetti et al., 2004).

From a heritability standpoint, values of as low as 0.10 were found in lambs (Vanimisetti et al., 2004) to has high as 0.55 (Assenza et al., 2014). PCV heritability ranged from 0.15 to 0.39 (Vanimisetti et al., 2004). While there is a considerable amount of variation, these moderate to strong heritability values indicate the ability for producers to select for and make genetic progress in reducing FEC, increasing PCV and increasing overall resistance to GIN. With low genetic correlations between FEC and BW (Brown and Fogarty, 2016), selection can be made to reduce FEC without negative effects on BW gain.

Heterosis

Heterosis is the advantage given to crossbred individuals above the average of their two purebred parents. In general, traits with a greater genetic component (higher heritability) have lower levels of heterosis.

Heterosis for FEC ranges from -2.1 to 0.5% (Hielscher et al., 2006) up to 33.8 to 81.6% (Li et al., 2001) depending on location and breeds utilized. Hielscher et al. (2006) utilized Merino Land and Rhoen sheep in Germany as compared to Li et al. (2001) who utilized SU and

Gulf Coast Native sheep in the southeastern U.S. PCV heterosis ranged from 0.5 to 2.1% (Hielscher et al., 2006) or 0 to 20.7% (Li et al., 2001). Actual worm counts ranged from 0.9 (Hielscher et al., 2006) to 4.6% (Li et al., 2001). Heterosis levels for FAMACHA score ranged from 1.9% during the primary infection to 9.4% during the secondary infection (Hielscher et al., 2006). Levels of heterosis for BW ranged from 1.2 to 3.8% (Li et al., 2001).

For producers utilizing crossbreeding scenarios, heterosis values of 33.8-81.6% for FEC in favor of the more resistant parent indicate a strong advantage that the F_1 progeny have over the average of their parents (Li et al., 2001). However, Hielscher et al. found a majority of the heterosis values were at or below 2% related to parasite infection (Hielscher et al., 2006). Further evidence is needed to make conclusions in regard to the specific value heterosis has to sheep producers in the area of parasite resistance.

Eimeria spp.

Eimeria species, a protozoan parasite, can cause BW loss and diarrhea in infected lambs. Typical infections occur more commonly in young lambs resulting from the consumption of oocysts on contaminated forage or water or by licking areas of fecal contamination (ASI, 2002). These oocysts result in production of sporozoites which initiate infection leading to damage to gut cells and the consequent disease symptoms. While there has been extensive work evaluating the mechanisms of disease and resistance to GIN, there are few papers evaluating these factors, particularly resistance, to *Eimeria* infections in sheep. Reeg et al. (2005) suggests variation in the proportions of *Eimeria* spp. present at different lamb ages. *E. ovinoidalis* was predominant in 17 to 40 d old lambs compared to *E. parva* which constituted the highest proportion from 80 to 100 d of age. Antibody levels were variable. Initially, there was only a slight genetic component to levels of oocyst excretion; however in lambs over 60 d of age, heritabilities were over 50 percent (Reeg et al., 2005).

Breed Differences

Breed and breed type variation in resistance to GIN has been documented. This variation is often a consequence of breed origin and development. Underlying the reduction in FEC and heightened PCV found in resistant breeds, immune mechanisms regulate the biological response to infection. Differences in immune response provide insight into the variation associated with the mechanisms of resistance to GIN.

Variation in resistance to GIN infection exists between hair and wool breeds (Vanimisetti et al., 2004b). This variation in resistance is a consequence of variation in immune response to GIN infection. In both hair and wool breeds, infection with *H. contortus* results in the characteristic Th2 type response (IL-5, IL-13 and IgE) with a reduction in IFN – γ expression. However, hair sheep demonstrated elevated levels of IL-13 in addition to FcεRI (MacKinnon et al., 2015) and IgE expression (Lacroux et al., 2006; Shakya et al., 2009). This enhanced IgE is related to the ability to more rapidly respond to infection (Lacroux et al., 2006) and FcεRI is an indicator of greater eosinophils. Further, there was upregulation of IL-4 (Jacobs et al., 2015, 2016; Shakya et al., 2009) and IL-5 (Jacobs et al., 2015, 2016) in addition to CXCL1, MCP1 and ARG1 (Schumacher et al., 1992). IL-5 is associated with activation of eosinophils (Clutterbuck et al., 1987) and CXCL1 is associated with the recruitment of neutrophils (Bowdridge et al., 2015). Additionally, hair sheep had greater eosinophil, neutrophil, globule leukocyte and mast cell levels (Shakya et al., 2009). In summary, hair sheep had a lesser Th1 response (IL-12 and IFN – γ) (Webb et al., 2007) and a greater Th2 response (Pernthaner et al., 2005b, 2006). This early Th2 type response is an indicator of greater adaptive immunity in the hair sheep. While the wool sheep also had a strong Th2 type response (Meeusen et al., 2005; Pernthaner et al., 2005b; Lacroux et al., 2006) with increased IL-10 (Shakya et al., 2009), they also had greater expression of IL-12 p 35 (Th1) (MacKinnon et al., 2015) and IFN-γ (Shakya et al., 2009). Adipogenesis, angiogenesis and tissue remodeling were also enhanced in wool breeds as indicated by greater PPaRγ (Toriseva et al., 2012), VEGF and PDFG (Benjamin et al., 2012) and MMP13 (Toriseva et al., 2012), respectively. This indicated a biological response to harm caused by the *H. contortus* infection in the wool sheep. Furthermore, there was enhanced expression of TNF – α and IL-6 which are associated with inflammation. These findings indicated an innate immunological advantage of hair sheep to resist and combat infection by *H. contortus.*

Effects of this enhanced immune response can be found in FEC and PCV analysis. Wool breeds demonstrated greater FEC and a reduced PCV compared to hair breeds (Shakya et al., 2009; Vanimisetti et al., 2004b). This indicates greater fecundity in the parasite population of wool breeds and a greater impact on the anemia status of the host.

Further evidence of variation in response to infection is found in differential gene expression. Genes differentially expressed in lymph nodes includes those associated with immune response along with apoptosis, receptors and transcription. Differential expression in abomasal tissue was associated with immune function, transcription, muscle function, calcium binding and transporters (MacKinnon et al., 2009).

These GIN resistance attributes (enhanced immune response and consequently reduced FEC and greater PCV) have allowed the hair sheep to adapt well to extensive forage-based production systems in warm and humid climates. This adaptation has resulted in their rise in popularity among commercial sheep producers in the southeastern U.S.

Texel and Suffolk Differences

The SU and TX breeds are potential terminal sire options for hair sheep producers. Consequently, the resistance of the crossbred offspring would be associated with their ability to perform in a forage based system. Research on resistance to GIN between these breeds is limited but suggests advantages to the TX breed. The TX had greater eosinophils levels as well as greater serum antibodies. In addition, there is a negative correlation between mucosal antibodies (IgE) and FEC. Additionally, TX lambs have greater corpuscular volume and nematode-specific antibody activity (Sayers et al., 2007). In SU sheep, there were greater leukocyte and pepsinogen levels indicating greater tissue damage (Sayers et al., 2007) as well as compromised IgE affinity (Sayers et al., 2005). Interestingly, SU lambs displayed greater PCV (Sayers et al., 2005). While both breeds had similar B haplotype frequencies at intron 1 of IFN-γ, in only the TX was it associated with resistance suggesting another locus linked to IFN-γ is instead responsible (Sayers et al., 2005). Between the SU and TX breeds, a greater immune response to GIN infection exists in TX sheep which in turn is related to their decreased FEC and abomasal worm count compared to the SU (Good et al., 2006). This enhanced resistance to GIN infection found in the TX breed has resulted in their consideration as terminal sires in extensive, forage-based, hair sheep production systems.

Conclusions

Internal parasites such as *H. contortus*, *T. circumcincta*, and *Trichostrongylus* spp. will continue to impact sheep production. As suggested by Bishop (2012), greater resistance of sheep to these parasites on an entire flock basis may result in decreased exposure due to lower pasture contamination. Nonetheless, for most producers, GIN will have an effect on their production systems. It will only be with continued research into innovative methods for control that the impacts may be lessened.

Due to the rise in anthelmintic resistance, alternatives to regular deworming must be established as the norm to decrease selection for anthelmintic resistance in the parasite population and increase the resistance of sheep to GIN. While there is variability in the type of response and the degree of those responses, there is a clear genetic component to the mechanisms of parasite resistance. Resistance is rooted in the ability of the immune system to respond to infection. The immune system's response is based on the expression of activated genes. These genes include signaling for Th1 and Th2 type responses. Greater expression leads to a greater immune response which allows the sheep to better respond to infection. Heritability for FEC and PCV range from 0.10 to 0.30 (Vanimisetti et al., 2004a) indicating a moderate ability to select for resistance in future generations. In addition, levels of heterosis were as high as 33.8 to 81.6% for FEC favoring the more resistant hair breeds. PCV heterosis ranged from 0-20.7%, and heterosis for worm count was 4.6% (Li et al., 2001). These levels of heterosis indicate potential in cross breeding scenarios to produce F_1 progeny with resistance more similar to their hair sheep ancestors. From a genetic perspective, selection of individuals with lower FEC and higher PCV has the potential to create future generations with similar levels of resistance. The evidence presented suggests the potential of genetics as a substitute for traditional anthelmintic use thereby decreasing prevalence of anthelmintic resistance and providing producers an alternative to maintain performance and profitability in their flocks.

Breed differences in growth and carcass characteristics

Introduction

In terms of growth and carcass merit, there are differences between the KT, SU and TX breeds. These differences can result in variation related to live and carcass value among the breeds. Traits which influence carcass value include live and carcass weight in addition to USDA Yield (12th rib back fat (FT) and body wall thickness (BWT)) and Quality (conformation, maturity, and flank streaking) Grades which are used as measures of primal cut quality.

Terminal sire breeds have been developed to excel in these attributes. Historically, the black-faced breeds (SU, Shropshire, Oxford) have been heavily utilized for this purpose. However, white-faced breeds which can serve this function also exist. These include the Dorset and TX. Following importation to the U.S. in 1985, the TX has been included in numerous studies at the U.S. Meat Animal Research Center (Leymaster and Jenkins, 1993; Shackelford et al., 2012) and the U.S. Sheep Experiment Station (Leeds et al., 2012; Mousel et al., 2012; Notter et al., 2012; Kirschten et al., 2013). These studies have evaluated the TX in comparison with other breeds in terms of growth and carcass merit as well as survivability to identify their potential as terminal sires in the U.S. Here, these attributes will be discussed as they relate to the performance of crossbred lambs.

Katahdin Carcass Characteristics

The KT breed was developed for its hardy, maternal characteristics with selection for hair, mothering ability and carcass merit. However, in comparison with traditional meat breeds, potential exists for improvement of KT carcass merit. Compared to terminal sire breeds (SU and TX) the KT-sired lambs had the lightest harvest BW at an age-constant endpoint. Additionally, KT-sired lambs had the greatest percentage of KPH, the greatest FT, the smallest LM area (LMA), and the lowest leg score (LS; Shackelford et al., 2012) on an age- and weight-constant basis. For these reasons, terminal sire breeds have the potential to improve the carcass merit of KT lambs in terms of carcass weight and muscling while reducing fat.

Birth weights

While BW at birth (BT) is an indicator of lambing ease, greater BW are associated with higher survivability (Leeds et al., 2012). However, in Ali et al. (2005a) no survival differences were found between the TX- and SU-sired lambs. In addition, growth traits such as BT, weaning (WWT) and post weaning (PWWT) BW are highly correlated (Lewis and Brotherstone, 2002; Notter et al., 2014). Differences in BT between SU- and TX-sired lambs have varied in significance. In studies conducted in the United Kingdom (U.K.) along with an initial study done in the U.S. evaluating the TX as terminal sires, no difference was found in BT between lambs sired by the respective breeds (Latif and Owen, 1979; Wolf et al., 1980; Leymaster and Jenkins, 1993; Ali et al., 2005a). However, in a more recent study, a difference between the breeds was observed with the SU-sired lambs being heavier at birth compared with the TX-sired lambs (Leeds et al., 2012). Additionally, SU-sired lambs tended to require greater assistance at birth compared to TX-sired lambs which could be attributed to this increase in BT (Leeds et al., 2012). This variation is BT differences may be associated with differences in breed type between the U.S. and the U.K.

Weaning Weights

In sheep enterprises, weaning can occur at varying ages depending on production system (Leymaster and Jenkins, 1993; Leeds et al., 2012). BW at weaning is a reflection of both the lamb’s genetic merit for growth but also the influence of maternal attributes. WWT and ADG to 16 weeks were not different for TX-sired lambs compared to other U.K. terminal sires (Cameron and Drury, 1985). This was also consistent with Latif and Owen (1979, 1980) where weaning occurred at 6 weeks. Further, Leymaster and Jenkins (1993) and Ali et al. (2005a) found no difference in WWT between SU- and TX-sired lambs. Additionally, there were no differences between the breeds for ADG prior to weaning (Ali et al. 2005a). In contrast, at 12 weeks of age, lambs sired by SU rams had greater WWT than TX-sired lambs in addition to greater ADG from 4 to 8 weeks (Wolf et al., 1980). In a range production system, SU-sired lambs were also heavier at weaning (Leeds et al., 2012). In Leymaster and Jenkins (1993), lambs were weaned at an average age of 51 d in a dry lot environment. In Leeds et al. (2012) lambs were weaned at approximately 132 d of age after being managed on rangeland. Consequently, these differences in age could explain the variation in BW observed at weaning.

Post-weaning weights

Post weaning performance is a reflection of the individual's ability to thrive without maternal assistance. The post weaning period is typically reflective of the time from weaning to the time of harvest or time to approximate harvest weight in breeding animals. Early studies in Ireland found BW differences at 14 weeks with the SU-sired lambs heavier than TX-sired lambs with greater ADG (More O'Ferrall and Timon, 1977). Further, Ellis et al. (1997) observed heavier SU-sired lambs at harvest than TX-sired lambs. However, in Latif and Owen (1979, 1980) there were no differences in growth during the post weaning period. In the U.S., Leymaster and Jenkins (1993) found greater BW at harvest in SU-sired lambs at all ages up to 189 d (Leymaster and Jenkins, 1993). Shackelford et al. (2012) observed a similar trend at 216 d of age. Similar results were also observed by Ali et al. (2005b) with SU-sired lambs heavier on an age-constant basis with greater ADG than TX-sired lambs. In a range production system, SU-sired lambs remained heavier than TX-sired lambs as well (Mousel et al., 2012). Not only were PWWT greater for the SU influenced lambs but this greater genetic merit for growth was also reflected in ADG over the post weaning period. In sheep from the range production system, ADG for SU-sired lambs was greater over the entire feeding period (Notter et al., 2012). Additionally, lambs sired by SU rams had greater G:F ratio while having a greater residual feed intake (RFI) during the first 45 d on feed and a greater cumulative residual gain over the 90 d (Kirschten et al., 2013). In contrast, no differences in feed efficiency were observed in a Midwest system (Ali et al., 2005b) or a European system (Latif and Owen, 1980). Evidence suggests the SU breed has a greater genetic merit for growth than the TX. This difference is reflected from birth to harvest. In a marketing system which rewards live BW, the SU-sired individuals would have an economic advantage. However, consideration must be given to BT if labor resources are limiting.

Carcass traits

Depending on the market system utilized, value can be assessed live or based on carcass merit. Studies prior to the arrival of the TX in the U.S. evaluated the TX compared to the SU and other breeds for their terminal-sire merit in the British Isles. Age at slaughter was less for the SU-sired lambs (More O'Ferrall and Timon, 1977; Wolf et al., 1980) while carcass weight was increased (More O'Ferrall and Timon, 1977) along with carcass weight for a given age (More O'Ferrall and Timon, 1977; Wolf et al., 1980). Additionally, the TX-sired lambs had a greater dressing percentage (DP; Wolf et al., 1980). In contrast, results from Latif and Owen (1979) indicated no differences in HCW or DP between the breeds. However, when higher-energy diets were fed, the TX-sired lambs had greater HCW and DP (Latif and Owen, 1980). Ellis et al. (1997) reported similar HCW and DP between the two sire breeds. While TX-sired lambs had reduced carcass length (More O'Ferrall and Timon, 1977; Ellis et al., 1997), they excelled the SU-sired lambs in terms of length of leg (More O'Ferrall and Timon, 1977). Additionally, the SU-sired lambs had a greater percentage of carcass weight between the 6th and 13th ribs (including the breast) while the TX-sired lambs had the advantage in percentage of carcass anterior to the 6th rib. The ratio of leg and loin weight compared to leg length favored SU-sired lambs over TX-sired lambs. However, it is cutability where TX-sired lambs excelled having a greater percentage of lean while also having a greater lean to bone ratio and LMA (More O'Ferrall and Timon, 1977, Wolf et al., 1980). Kempster et al. (1987) compared lambs at the same subcutaneous fat cover from early (grass finished) and late flocks (grass, forage crops and roots) and found greater lean weight in the TX-sired lambs than SU-sired. In the late flocks, the TX-sired lambs also had less separable fat and greater LM depth. In terms of lean quantity and lean to bone ratio, the lambs sired by TX rams were superior to those sired by SU rams. There were no differences in distribution of lean (Croston et al., 1987). Similar results were found by Latif and Owen (1979 and 1980) where TX-sired lambs produced leaner carcasses with greater lean and bone weight in addition to less intermuscular and subcutaneous fat. This was further supported by Ellis et al. (1997) who reported greater lean to bone and lean to fat ratios in TX-sired lambs in addition to less total fat and a greater percentage of lean. Further, there were no differences in sensory evaluation (Ellis et al., 1997).

While growth potential favors the SU, the TX excels in muscling traits. In studies from the U.S., TX-sired lambs had greater LS than the SU-sired lambs (Leymaster and Jenkins, 1993; Shackelford et al., 2012; Mousel et al., 2012) and no differences were found in LMA (Leymaster and Jenkins, 1993; Partida et al., 2012). SU-sired lambs had less FT at 105 and 147 d of age; however, no differences were found at older ages (Leymaster and Jenkins, 1993; Shackelford et al., 2012; Mousel et al., 2012). This is contrary to the assumption that the larger framed SU breed would have less fat at heavier BW than the smaller framed TX. Lambs sired by SU rams had greater HCW (Leymaster and Jenkins, 1993; Shackelford et al., 2012; Mousel et al., 2012; Partida et al., 2012). This relationship is expected given the heavier BW at harvest of the SU – sired lambs. DP between the breeds would therefore be similar. There were no differences in

KPH between the sire breeds (Leymaster and Jenkins, 1993; Shackelford et al., 2012; Mousel et al., 2012) as well as no differences in USDA Quality Grade (Leymaster and Jenkins, 1993). Additionally, TX-sired lambs had reduced LM shear force while SU-sired lambs had lower lamb flavor intensity when adjusted to constant harvest age. No differences in sensory evaluation where determined when adjusted to constant carcass weight (Shackelford et al., 2012).

In addition to carcass weight advantages, the SU-sired lambs also excelled in carcass component weights. Rack, loin, sirloin and leg weights were heavier in SU-sired lambs than lambs sired by Columbia, Composite or TX sires. However, the trimming loss from these high value (HV) cuts was also greater. Consequently, the percentage of trimmed HV cuts did not differ between sire breeds. Additional lower valued cuts such as the shoulder, breast, and flank were also heavier in lambs sired by SU rams (Mousel et al., 2013).

Conclusions

While the KT breed has strong maternal attributes, it lacks the growth, muscle and leanness of terminal sire breeds. The TX and SU have been considered as terminal sire breeds for hair sheep production systems. While the SU has advantages in growth characteristics (BT, WWT and PWWT) they have a lower survival percentage at low BT and require a greater assistance at birth. In addition, the SU has reduced FT. The TX excels in muscling traits such as LS and lean to bone ratio. While the SU and TX breeds vary in terms of their respective carcass merit advantages, both breeds offer advantages to the KT breed. Other factors such as parasite resistance must be considered.

Summary

Despite the challenges associated with internal parasites, sheep production in the southeastern U.S. has experienced positive growth. A strong non-traditional market drives selection for sheep of moderate mature size and provides a reliable consumer, particularly near holidays. Consequently, hair sheep have adapted well to the extensive forage-based production systems of the southeast U.S. These breeds and their derivatives have a greater natural resistance to GIN. However, areas of improvement exist in these breeds in terms of growth and carcass merit. The TX and SU breeds are potential terminal sire options for hair sheep producers. In studies evaluating these breeds, the SU-sired lambs excelled in growth traits such as WWT and PWWT and ADG. The TX-sired lambs demonstrated superior lean to bone and lean to fat ratios in addition to LS. While both the TX and SU breeds have shown potential to enhance the growth and carcass merit of KT sheep, the TX breed has greater resistance to GIN. Resistance traits have a moderate genetic component. TX-sired F_1 progeny which retain resistance to GIN have the potential to improve growth and carcass characteristics of hair sheep in a forage-based production system thereby increasing the value of market lambs produced.

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Chapter II: Evaluation of terminal sire breeds for hair sheep production systems

Andrew R. Weaver

INTRODUCTION

Gastrointestinal nematodes (GIN) pose a significant health and economic burden to sheep producers. In 2009, death losses alone accounted for 2.8 million dollars (USDA-ASB-NASS, 2010). Additionally, decreased BW gains, milk yield and wool growth (Mavrot et al., 2015) result in substantial impacts to farm economic sustainability. *Haemonchus contortus*, or the Barber Pole Worm, is the most prevalent GIN in the Southeastern United States (U.S.; Howell et al., 2008). This abomasal nematode consumes blood from the host resulting in anemia. Severe infections can result in death of the host. Other GIN relevant to the small ruminant species include *Trichostrongylus* spp. and *Telodorsagia* spp. Traditional methods of GIN control utilizing routine deworming of all individuals have resulted in selection for anthelmintic resistance in GIN populations (Kaplan, 2004). Howell et al. (2008) observed resistance to three classes of anthelmintics on 42% of farms surveyed. With this decline in efficacy of chemical controls, new innovative methods of GIN management must be explored.

Sheep of Caribbean origin and their relatives have shown enhanced resistance to GIN quantified by fecal egg count (FEC) and packed cell volume (PCV; Vanimisetti et al., 2004a). These resistance indicators are moderately heritable (Vanimisetti et al., 2004b). Developed in Maine from crosses of “African Hair Sheep” and wool breeds, the Katahdin (KT) has maintained a level of GIN resistance from their hair sheep ancestors. This combination of maternal attributes, GIN resistance and a strong non-traditional market (USDA-AMS, 2016) has resulted in the KT's rise in popularity among commercial sheep producers in the Southeastern U.S. over the last 10 years**.**

Despite their easy-care attributes, traditional wool breeds excel the KT in terms of growth traits and carcass merit (Shackelford et al., 2012). Consequently, terminal sire breeds could increase the value of market lambs produced, so long as progeny maintain a level of resistance to GIN which would allow them to thrive in an extensive production system. The TX was first imported to the U.S. from Finland and Denmark in 1985 (Leymaster and Jenkins, 1993). With exceptional muscling characteristics, the TX may provide added premiums resulting from increased carcass cutability. In addition, evidence suggests the TX possesses GIN resistance greater than that of the SU (Good et al., 2005) while maintaining a more moderate frame size (Leeds et al., 2012). Provided the imported TX carried this enhanced level of resistance, the TX breed in the U.S. could have fitness advantages over the SU in extensive forage-based production systems.

Therefore, the objective of this study was to evaluate the TX as a terminal sire option for hair sheep ewe flocks to improve growth and carcass characteristics of market lambs while maintaining a level of GIN resistance required to thrive in this environment. When compared to the SU, the TX is expected to increase muscling traits while reducing GIN burden and consequently reducing anthelmintic treatment of lambs.

MATERIALS AND METHODS

Breeding Scheme

In year one (Y1), KT ewes (n = 61, 21, 18, respectively) were randomly bred to KT (n = 3), SU (n =1) and TX (n = 1) rams resulting in the birth of KT-sired purebred lambs (n = 90), SU-sired crossbred lambs (n = 43) and TX-sired crossbred lambs (n = 36). At weaning, 85 KT-sired lambs, 34 SU-sired lambs, and 34 TX-sired lambs remained. Four lambs were stillborn (SU-sired, n = 3; TX-sired, n = 1). One SU-sired lamb was removed due to mastitis in the dam. Remaining lambs were lost in the first 7 d after birth.

In year two (Y2), KT ewes (n = 40, 19, 22, respectively) were randomly mated to KT rams (n = 2), SU rams (n = 2) or TX rams (n = 2) resulting in 80 KT-sired, 37 SU-sired, and 46 TX-sired lambs. One KT sire from Y1 was utilized in Y2. New SU- and TX- sires were utilized in Y2. At weaning, 65 KT-sired, 35 SU-sired, and 43 TX-sired were utilized for post weaning performance evaluation. One lamb (SU-sired) born stillborn required assistance and was excluded from the data set. Death loss before 7 d of age was greater than after 7 d of age (KT-sired, n = 3 vs. 2; SU-sired, n = 1 vs. 0, TX-sired, n = 2 vs. 1; respectively). One KT-sired lamb was born 25 d after the conclusion of lambing and was excluded from the data. Additional lambs determined to be unfit for post grazing evaluation were removed.

Management

All animal procedures were approved by the Institutional Animal Care and Use Committee (No. 15-133) of Virginia Tech. Ewes and lambs were managed at the Southwest Virginia Agriculture Research and Extension Center (Glade Spring, VA). Breeding began in mid-October. At the conclusion of breeding, ewes were managed as one group on fescue-based mixed pasture and harvested forages until lambing.

In Y1, lambing began on March 16 and lasted 37 d. Average lambing date was March 26. In Y2, lambing began on March 9 and lasted 19 d. Average lambing date was March 18. Lambing occurred in a barn and ewe-lamb pairs were isolated (jugged) for approximately 24-48 hours after parturition. Upon removal from the jug, pairs were randomly assigned to a dry lot or pasture group. The dry lot group (Y1: KT-sired, n = 47; SU-sired, n = 14; TX-sired, n = 12; Y2: KT-sired, n = 7; SU-sired, n = 13; TX-sired, n = 11) was managed to minimize exposure to GIN and upon weaning, were transported to West Virginia University (Morgantown, WV) for an artificial infection trial in a raised floor barn. The pasture group was managed on fescue-based mixed pasture as one group until weaning. In Y1, weaning occurred on June 4, at an average age of 70 d. In Y2, weaning occurred on June 7 at an average age of 81 d. All pairs were treated for coccidiosis as necessary on a flock basis.

At weaning, lambs (Y1: KT-sired, n = 38; SU-sired, n = 20; TX-sired, n = 22; Y2: KT-sired, n = 58; SU-sired, n = 22; TX-sired, n = 32; Table 1) were moved to ungrazed pasture and managed as a single group for a summer grazing trial lasting approximately 90 d. BW, FEC, PCV (Y2 only) and FAMACHA score were recorded biweekly (Table 2a, 2b). In Y1, traits were recorded at weaning, in early July and then biweekly for the remainder of the grazing trial. An intermediate FAMACHA score was taken August 17 as lambs had signs of haemonchosis. In Y2, traits were recorded at weaning and then biweekly for the remainder of the grazing trial. Lambs were selectively treated with anthelmintic (FAMACHA ≥ 3) with levamisole (8 mg/kg) or moxidectin (0.2 mg/kg). In Y1, fecal egg count reduction test (FECRT) could not be calculated due to one treatment without FEC measured. In Y2, FECRT following moxidectin treatment was -12.4%. Levamisole (FECRT: 43.2%) was utilized when the lack of moxidectin efficacy was realized. Lambs were supplemented with a concentrate pellet (2% BW as fed, 13% CP, 75% TDN) during the grazing trial. Coccidiosis treatments with Corid® occurred as necessary on a flock basis. In Y1, the summer grazing trial ended on August 31. In Y2, the trial ended August 30.

FEC and PCV were analyzed at the Virginia-Maryland College of Veterinary Medicine Center for Molecular Medicine and Infectious Diseases (Blacksburg, VA). FEC were performed following the Modified McMasters method (Whitlock, 1948). Each egg counted represented 50 eggs per gram and samples of less than 2 g were not utilized. PCV was determined utilizing the microhematocrit centrifuge method with blood collected from the jugular vein.

Following the summer grazing trial, all lambs were treated with anthelmintic and a post grazing (finishing) period began. Lambs within one SD of the average BW at the conclusion of the grazing season were maintained for finishing evaluation (Table 3). In Y1, lambs (12 KT-sired, 10 SU-sired, and 11 TX-sired) were maintained on pasture for four months and provided a concentrate ad libitum. In months five and six post grazing, lambs were placed in a dry lot and fed ad libitum until harvest (Feb. 24) at approximately 11 months of age. In Y2, lambs (15 KT-sired, 14 SU-sired, and 15 TX-sired) were moved to dry lot at the conclusion of the grazing trial until harvest (Dec. 1) at approximately nine months of age. Two SU-sired lambs outside of one SD were utilized to ensure an equal number of lambs were represented per breed. BW were recorded approximately every four weeks to ensure adequate growth was maintained. Harvest was determined when lambs reached an average live weight (LW) of 50 kg.

Carcass evaluation

Three lambs of each breed type and sex were randomly selected from ± one SD of the average BW (Tables 1 and 3). Lambs were transported to the Virginia Tech campus 24 hours before harvest and provided water and free choice hay. Lambs were transported to the Virginia Tech Meat Center the next morning for harvest. LW were recorded prior to transport. HCW were recorded following harvest and included KPH. Dressing percentage (DP) was calculated as

(HCW/LW) X 100. Carcasses were allowed to chill for 24 hours before ribbing and carcass evaluation.

Carcasses were ribbed between the 12th and 13th rib. Twelfth-rib fat thickness (FT) was determined half the distance across the LM perpendicular to the exterior of the carcass. Body wall thickness (BWT) was measured 13 cm from the center of the vertebrae perpendicular to the exterior of the carcass. LM area (LMA) was determined at the 12th rib. Measurements for FT, BWT and LMA were determined on each half of the carcass and averaged (Boggs et al., 2006). Adjusted 12th rib fat thickness (ADJFT) was determined as ADJFT = [((1/2) X BWT in cm – 0.3556) + FT] / 2. Yield grade (YG) was determined based on the ADJFT (YG = 3.94 X ADJFT in cm + 0.4; Boggs et al, 2006). Conformation (leg score, LS; Prime$^+$ = 15; Cull = 1) was assessed according to USDA (1992) standards. Quality Grade (QG) was accessed based on flank streaking, maturity and conformation in accordance with the AMSA guidelines (AMSA, 2001). KPH weight was determined and analyzed as a percentage of HCW. The percentage of boneless, closely trimmed retail cuts (BCTRC) from the shoulder, rack, loin and leg were determined based on Savell and Smith (1998) as BCTRC = 49.936 – (0.1866 X carcass weight (kg)) – (1.723 X FT (cm)) – (1.39 X BWT (cm)) + (0.3807 X LMA (cm^2)).

In Y2, primal cuts were analyzed. Institutional Meat Purchase Specifications (IMPS; USDA, 1996) were used to cut the square-cut shoulder (IMPS 207), rib rack (IMPS 204), 4 X 4 loin (IMPS 232) and leg (IMPS 233A). These were weighed and analyzed as a percentage of chilled carcass weight (CCW). Primal values were determined (USDA Weekly National Lamb Market Summary; Dec. 2, 2016). Carcass value was determined in terms of these high value (HV) cuts.

Y1 ram lambs were kept intact and all lambs were housed together. At harvest, eight of nine ewe lambs were pregnant (single or twins) with total fetus weight ranging from 1.4 to 12.7 kg. LW and HCW were adjusted to reflect open individuals. In Y2, ram and ewe lambs were housed separately after grazing. Ewe lambs received an injection of Lutalyse® post grazing. At harvest, all Y2 ewe lambs were open.

Statistical analysis

Statistical analysis was performed utilizing SAS (SAS Institute Inc., Cary, NC). All analyses were done within-year due to time differences in measurement points between years. Sire was not included in the models due to the limited number represented per breed. For data recorded at or before weaning, number of lambs born (NLB), number of lambs weaned (NLW) and lamb loss (LL) along with their respective ewe age-adjusted values (ADJNLB, ADJNLW, ADJLL) were evaluated on a per ewe basis. Birth weights (BT) and weaning weights (WWT) were evaluated per lamb by sire breed. BT was adjusted (ADJBT) for NLB, ewe age and sex. WWT was adjusted (ADJWWT) to 60 days of age and for NLB, NLW, ewe age and sex. Sire breed effects for all birth and weaning data were analyzed utilizing Proc GLM. Tukey's test was used for separation of least-squares means. Significance was determined at $P < 0.05$. Correlations between growth measurements were analyzed using Proc CORR.

Post weaning weights (PWWT) were adjusted (ADJPWWT) to 165 days of age (i.e., to conclusion of grazing trial) and for NLB, NLW, ewe age and sex. FEC were transformed as lnFEC = ln(FEC+100) to improve the normality for the FEC distribution. A repeated-measures analysis using Proc MIXED was utilized to analyze effects of sire breed, sex and time (the repeated factor) on growth during the grazing period and indicators of parasite resistance (FEC, FAMACHA, and PCV). Interactions of breed and time and sex and time were also included in the model. In Y1, the covariance structure for the repeated measures was assumed to follow a pattern of compound symmetry (CS), as measurements were not recorded at equal time intervals. In Y2, a first-degree autoregressive covariance structure was utilized. Sire breed and sex effects at each measurement and overall ADG were analyzed with Proc GLM. Tukey's test was used for separation of least-squares means. Deworming (anthelmintic treatment) records were analyzed as cumulative deworming and deworming frequency. Cumulative deworming represented the proportion of lambs treated per sire breed prior to and including that time point. Only lambs which had not been treated were included in the FEC, FAMACHA and PCV evaluations. Deworming frequency ranged from one to three times. Proc GENMOD was utilized for binomial analysis of deworming data by time with effects of sire breed. For time points when one or more sire breed groups had zero lambs treated, SEM could not be calculated and no Chi-square value was determined. Correlations (Proc CORR) between resistance indicators and ADG were determined and regressions (Proc REG) fitted for each indicator and ADG. Contrasts were utilized to test for heterogeneity of regression coefficients among sire breeds.

Post grazing weights and ADG were analyzed using Proc MIXED and a model that included effects of sire breed, sex and time and assumed a CS covariance structure for the repeated measures. Interactions of breed and time and sex and time were also included. Sire breed and sex effects at each measurement and overall ADG were analyzed utilizing Proc GLM. Carcass traits were analyzed using Proc GLM with a model that included effects of sire breed and sex. Primal cut weights (shoulder, rack, loin, and leg) were evaluated as a percentage of CCW. Tukey's test was utilized for separation of least-squares means. Correlations between carcass measurements were analyzed using Proc CORR.

RESULTS AND DISCUSSION

Pre-weaning performance: Birth and survivability

In Y1, ADJBT did not differ between sire breeds (Table 4). No differences existed between males and females for ADJBT (Table 5). Ewe ages ranged from 3 to 8 years. Average ewe ages ranged from 4.4 years for ewes raising TX-sired lambs to 5.9 year for ewes raising KT-sired lambs. No differences existed for ADJNLB or ADJNLW (Table 4). There were no observed differences in lambing difficulty and no differences in ADJLL. Death losses occurred primarily within 5 d of birth. No differences existed in birth data prior to adjustment.

In Y2, SU-sired lambs had the greatest ADJBT ($P < 0.05$; Table 4). One SU-sired lamb (BT = 8.2 kg) was stillborn and required assistance at lambing and was removed from the data set. There were no other observed differences in lambing difficulty. Ewe lambs were heavier at birth ($P < 0.001$; Table 5). ADJNLB and ADJNLW did not differ between sire breeds (Table 4). Ewe age range between sire breeds in Y2 was 0.5 years. There were no differences in LL per ewe lambing. The majority of LL occurred within the first 7 d.

Y2 BT results are in agreement with those reported by Leeds et al. (2012) and Ali et al. (2005) when BT of SU-sired lambs were adjusted to a single lamb basis. The absence of differences in Y1 are supported by Leymaster and Jenkins (1993), More O’Ferrall and Timon (1977), and Latif and Owen (1979). Here, no differences in BT were observed. SU-sired lambs would be expected to have greater BT due to their additional frame size and mature weight (Leeds et al., 2012). The similarity in BT detected in Y1 could be attributed in part to the genetic merit of individual sires. SU sires utilized in this study were more moderate in their type compared to traditional western-range terminal sires (Average PWWT EBV = 4.58 kg, 30th percentile). Within-breed variation and sire selection may have contributed to BT similarities.

Ram lambs would be expected to have greater BT than ewe lambs (Latif and Owen, 1979). The greater BT of ewe lambs in Y2 could be explained by ewe lambs born into smaller litter sizes. Average litter size for ewe lambs was 2.08 compared to 2.24 for ram lambs ($P = 0.15$). Adjusting BT for sex would further separate differences as the BT adjustment for sex is greater for ewes than rams. In both Y1 and Y2, NLB and NLW did not differ between sire breeds. While the ewe flock was of similar genetic base and ewes were randomly allocated to breeding groups, lamb heterosis would suggest a NLW increase of approximately 15% for the terminal-sired lambs (ASI, 2002). Leymaster and Jenkins (1993) reported a tendency for increased death loss of SU-sired lambs prior to weaning with primary losses at birth. Further results from Leeds et al. (2012) indicated a diminished probability of survival for SU-sired lambs born under breed average for BT. No differences in survival rate were reported by Ali et al. (2005). Little difference was observed in lambing assistance between ewes carrying SU- or TX-sired lambs (Leeds et al., 2012).

Pre-weaning performance: BW and ADG

In Y1, average weaning age was 70 d. KT-sired lambs had the lightest ADJWWT compared to both TX-sired ($P < 0.001$) and SU-sired lambs ($P < 0.05$; Table 4). These weights are reflective of greater ADJWADG for TX-sired lambs compared to KT-sired lambs ($P < 0.001$). SU-sired lambs tended to have greater ADJWADG compared to KT-sired lambs ($P = 0.052$). No sex differences existed in ADJWWT or ADJWADG (Table 5). Physiological differences between ram and ewe lambs were accounted for in adjustment factors. Correlations between BT and WWT were similar prior to and after adjustment (0.59 vs. 0.53, respectively; $P < 0.001$).

In Y2, average weaning age was 81 d. KT-sired lambs were lighter than both SU- and TX-sired lambs ($P < 0.05$) for ADJWWT (Table 4). When ADG was determined from adjusted weights, KT-sired lambs had reduced ADG compared to SU-sired lambs ($P < 0.05$) and tended to grow slower than TX-sired lambs ($P = 0.06$). Ewe lambs had greater ADJWWT than ram lambs ($P < 0.01$); however, there were no differences in ADJWADG between ram and ewe lambs (Table 5). Correlation between BT and WWT was 0.48 ($P < 0.001$), and this relationship decreased when adjusted weights were utilized ($r = 0.39$, $P < 0.001$).

The reduced growth performance at weaning of KT-sired lambs in both years would be expected due to their lighter BW at maturity (Shackelford et al., 2012). In extensively managed systems, SU-sired lambs had greater WWT compared to TX-sired lambs (Leeds et al., 2012; Ali et al., 2005; More O'Ferrall and Timon, 1977). Latif and Owen (1979) observed no breed differences at six weeks of age. In an intensive system, SU- and TX- sired lambs did no differ in WWT (Leymaster and Jenkins, 1993). As noted by Leymaster and Jenkins (1993), variation between individual sires within a breed could contribute to differences between breed averages based on sires utilized. The greater WWT of TX-sired lambs in Y1 may have resulted from superior Texel genetics. In both years, no differences were observed between sexes for pre-weaning ADG. Ewe lambs were reared in litters containing 0.14 more lambs than ram lambs ($P = 0.22$). ADJWWT were consequently greater due to the larger associated adjustment. Safari et al. (2007) observed similar correlations between BT and WWT ($r_g = 0.44$, $r_p = 0.32$). The adjustment of WWT based on NLW may have affected the relationship between ADJWWT and ADJBT.

Grazing performance: BW and ADG

Y1 grazing evaluation constituted 88 d post weaning. Average lamb age at the conclusion of the grazing trial was 158 d. For comparisons between years, lamb age was adjusted to 165 days. TX-sired lambs had greater ADJPWWT than KT-sired lambs ($P < 0.001$) and tended to have greater BW than SU-sired lambs ($P = 0.07$; Table 4). Lambs sired by TX rams also had greater ADJPADG during the grazing trial compared to KT-sired lambs ($P < 0.05$) and tended to have increased ADG compared to SU-sired lambs ($P = 0.08$). BW and ADG during the grazing trial are reported in Table 6. No differences in ADJPADG existed between ram and ewe lambs (Table 5). ADJPWWT of ram lambs at the conclusion of the grazing season tended to be greater than ewe lambs ($P = 0.08$) as a result of greater pre-weaning growth. WWT and ADJWWT were highly correlated with PWWT and ADJPWWT (r = 0.83 and 0.74, respectively; $P < 0.001$). BT and ADJBT were moderately correlated with PWWT and ADJPWWT (r = 0.45 and 0.30, respectively; $P < 0.01$).

In Y2, the grazing trial was 84 d and average lamb age at the end of the trial was 165 d. No differences existed between sire breeds for ADJPWWT at the conclusion of the grazing trial (Table 4). ADJPADG between sire breeds did not differ. ADJPWWT of ram lambs was not different than ewe lambs and no differences existed between the sexes for ADJPADG (Table 5). WWT and ADJWWT were highly correlated with PWWT and ADJPWWT (r = 0.80 and 0.74, respectively; $P < 0.001$). BT were lowly correlated with PWWT (r = 0.32, $P < 0.001$); however, after adjustment, little linear relationship existed (0.21, $P < 0.05$).

The trend in PWWT across sire breeds remained similar to that of WWT in Y1 with TX-sired lambs remaining superior. These results conflict findings of previous studies. However, prior literature on post weaning performance largely evaluated differences in an intensive management environment. In general, the growth performance of SU-sired lambs has been superior during the post weaning period (Ali et al., 2005; Notter et al., 2012; Leymaster and Jenkins, 1993; More O'Ferrall and Timon, 1977). Latif and Owen (1979) found no growth differences from six weeks to slaughter for SU- and TX-sired lambs. More O'Ferrall and Timon (1977) along with Latif and Owen (1979) were the only two studies utilizing forage based management systems. The absence of differences in BW or ADG in Y2 compared to Y1 would indicate possible individual sire effects. Variation within breed would increase the importance of sire selection for representative breed performance. Ram lambs have greater ADG than ewe lambs (Latif and Owen, 1979). In both years, no differences in ADG were observed between sexes; however, BW of ram lambs was greater post weaning. In Y1, the trend in WWT continued in PWWT. In Y2, while ADJWWT was greater for ewe lambs this difference diminished by 165 d. WWT and PWWT correlations are supported by Notter et al. (2014; $r_g = 0.90$). In Merino sheep, BT and yearling weights were also lowly correlated ($r_g = 0.16$, $r_p = 0.34$; Safari et al., 2007). The addition of NLW and age adjustments to ADJPWWT may have affected its relationship with BT and ADJBT.

Grazing performance: Parasite resistance

In Y1, FEC varied over time ($P < 0.001$; Table 7, Figure 1a). There were no differences between the sire breeds for FEC and no interaction between time and breed. Average FEC over the summer grazing trial tended to be greater for TX-sired lambs compared to KT-sired lambs ($P = 0.106$). FAMACHA scores did vary by sire breed ($P < 0.01$) and time ($P < 0.001$). There was also an interaction of sire breed and time ($P < 0.05$). FAMACHA scores at the start of the grazing trial were greater for TX-sired lambs than KT-sired lambs ($P < 0.01$). When scores were averaged over the grazing period, KT-sired lambs had reduced FAMACHA scores compared to TX- and SU-sired lambs ($P < 0.01$). Sire breed influenced the proportion of lambs dewormed mid-summer with KT-sired lambs requiring less anthelmintic treatment compared to TX-sired lambs ($P < 0.05$; Table 8). At the end of the grazing season, a greater proportion of SU-sired lambs tended to require anthelmintic treatment compared to KT-sired lambs ($P = 0.054$) and TX-sired lambs ($P = 0.10$). Additionally, there was a sire breed difference in the proportion of lambs requiring multiple dewormings ($P < 0.05$) with the greatest proportion of TX-sired lambs being treated three times. Death losses during Y1 grazing were 5% for KT-sired lambs.

Ram lambs had greater FAMACHA scores than ewe lambs ($P < 0.05$; Table 9). FAMACHA score varied over time ($P < 0.001$); however, there was no interaction of sex and time. FAMACHA scores tended to be greater for ram lambs mid-summer ($P = 0.099$). No differences existed at other time points. When breed, sex and time along with their interactions were fitted for FAMACHA score, breed ($P < 0.01$), sex ($P < 0.05$) and time ($P < 0.01$) all influenced FAMACHA score. There tended to be an interaction between breed and sex ($P = 0.08$). No other interactions existed. KT-sired lambs had the lowest FAMACHA scores ($P < 0.05$). Ram lambs had greater FAMACHA scores ($P < 0.05$).

In Y2, FEC varied over time ($P < 0.001$; Table 7, Figure 1b). FEC did not differ between sire breeds; however, there was a tendency for an interaction between sire breed and time ($P = 0.09$). Sire breed tended to influence FAMACHA score ($P = 0.06$) and FAMACHA score varied over time ($P < 0.001$). There was no interaction of FAMACHA score and time. KT-sired lambs tended to have lower FAMACHA scores compared to SU-sired lambs ($P = 0.053$). SU-sired lambs had greater FAMACHA scores compared to both TX- and KT-sired lambs at the start of the grazing trial ($P < 0.05$). Mid-summer, KT-sired lambs had lower FAMACHA scores compared to TX-sired lambs ($P < 0.05$). PCV varied over time ($P < 0.001$); although there were no differences between the sire breeds for PCV. There was an interaction between sire breed and time for PCV ($P < 0.05$). Sire breed influenced the proportion of lambs dewormed at initial sampling ($P < 0.05$; Table 8) with SU-sired lambs requiring the greatest treatment. At the start of the third week, a greater proportion of SU-sired lambs had been dewormed compared to TX-sired lambs ($P < 0.05$). Mid-summer, sire breed tended to influence deworming proportion ($P = 0.08$) with KT-sired lambs requiring the least treatment. At the end of the grazing trial, the tendency for sire breed to influence anthelmintic treatment continued ($P = 0.08$) with the proportion of lambs which required deworming lowest for KT-sired lambs compared to SU- and TX-sired lambs ($P = 0.06$ and 0.08; respectively). No differences existed between sire breeds for the proportion of lambs which only required one or two anthelmintic treatments. A greater percentage of SU-sired lambs required three treatments compared to KT-sired lambs ($P < 0.05$) and a tendency existed compared to TX-sired lambs ($P = 0.10$). Death losses during Y2 grazing were 5% for KT-sired lambs and 9% for SU-sired lambs.

With FAMACHA ≥ 3 utilized as the basis for deworming, KT-sired lambs took a greater number of days before requiring anthelmintic treatment compared to TX-sired lambs (Y1, $P < 0.05$; Table 10) with SU-sired lambs intermediate. However, in Y2 lambs sired by TX rams tended to take a greater number of days before requiring deworming than SU-sired lambs ($P = 0.051$) with KT-sired lambs intermediate. Additionally, SU-sired lambs had the lowest FEC at the time of deworming ($P < 0.05$) with a PCV approximately 2% greater than that of KT- and TX-sired lambs (NS).

Across sire breeds, lnFEC was positively related to FAMACHA score ($r = 0.33$, $P < 0.001$) while negative relationships existed for PCV ($r = -0.52$, $P < 0.001$) and ADG ($r = -0.15$, $P < 0.001$; Table 11a). FAMACHA score was negatively correlated with both PCV ($r = -0.46$, $P < 0.001$) and ADG ($r = -0.21$, $P < 0.001$) while no relationship existed for PCV and ADG. For SU-sired lambs, no relationship existed between ADG and lnFEC or FAMACHA score. KT- and TX-sired lambs followed similar trends as across breed relationships. lnFEC of KT-sired lambs was more sensitive to changes in PCV than SU- or TX-sired lambs (β_1 = - 0.11 vs. -0.07 and -0.08; respectively, $P < 0.01$; Table 12a). However, no differences existed when PCV was regressed on lnFEC.

Sex differences were compared across sire breeds. Ram lambs tended to have greater FEC than ewe lambs ($P = 0.07$; Table 9). FEC varied over time and there was no interaction of sex and time. When the effects of breed, sex and time were fitted along with the two and three way interactions, sire breed and sex did not influence FEC. FEC did vary over time ($P < 0.001$). There was an interaction of breed and time ($P < 0.05$). No other interaction existed.

Sex had no effect on FAMACHA score (Table 9). FAMACHA score varied over time ($P < 0.001$) and there was no interaction of sex and time. When the effects of breed, sex and time along with the two and three way interactions were fixed for FAMACHA score, sire breed influenced FAMACHA score ($P < 0.01$) along with sex ($P < 0.05$). However, there was an interaction of breed and sex ($P < 0.01$). FAMACHA score varied over time ($P < 0.001$). SU-sired lambs had greater FAMACHA scores than KT- and TX-sired lambs ($P < 0.05$). Ram lambs had greater FAMACHA scores than ewe lambs ($P < 0.05$). KT-sired rams and ewes were most similar in their FAMACHA scores. SU-sired ram and ewe lambs differed the greatest. TX-sired ewe lambs had greater FAMACHA scores than their ram lamb contemporaries.

Ewe lambs tended to have greater PCV than ram lambs ($P = 0.07$; Table 9). PCV varied over time ($P < 0.001$) and there was an interaction of sex and time ($P < 0.05$). Ewe lambs had greater PCV at all time points except 6 with significant differences mid-summer ($P < 0.05$). When the effects of breed, sex and time along with their two and three way interactions were fitted, sire breed did not affect PCV. PCV was influenced by sex ($P < 0.05$) and varied over time ($P < 0.001$). There was an interaction of breed and time ($P < 0.05$). No other interactions were significant. Ewe lambs had greater PCV than ram lambs ($P < 0.05$).

At the time of deworming, no significant differences existed between the sexes for resistance indicators (Table 10). However, in Y1 ram lambs required anthelmintic treatment 8 d prior to ewe lambs ($P < 0.05$). In Y2, ram lambs were dewormed 6 d sooner than ewe lambs while have a having a PCV 2% higher and a FEC approximately 1000 eggs/g less than that of ewe lambs at deworming (NS).

Vanimisetti et al. (2004b) characterized the differences between sheep of Caribbean origin and more traditional breeds for parasite resistance quantified by FEC and PCV. The enhanced resistance observed in KT-sired lambs was supported here. Despite the absence of differences in FEC, KT-sired lambs tended to have lower FAMACHA scores and required less anthelmintic treatment. Between the terminal-sired lambs, previous results would suggest advantages to TX-sired lambs (Good et al., 2005) in terms of FEC. This reduction in FEC was associated with the IFN- intron 1 microsatellite and the ‘A’ SNP variation in TX but not SU sheep (Sayers et al., 2005). While no FEC differences were observed, deworming results differed between sire breeds. In Y1, TX-sired lambs initially required the greatest deworming; however, as the grazing trial progressed, the percentage dewormed remained more constant as opposed to the SU-sired lambs which required the greatest deworming as the trial completed (Figure 1a). Differences observed in Y2 were more similar for TX- and SU-sired lambs yet at deworming, SU-sired lambs had approximately half the FEC of TX- and KT-sired lambs. The ability of TX- and KT-sired lambs to maintain a greater GIN population, yet resist clinical signs of parasitic gastroenteritis may be indicative of greater resilience (Hayward et al., 2014). The difference in days to deworming between Y1 and Y2 may be an effect of individual sire variation and annual environmental differences. This hypothesis would be further supported by the initial large proportion of TX-sired lambs requiring deworming in Y1 yet not in Y2. The proportion of lambs dewormed in Y2 increased at a more gradual rate before plateauing during the middle portion of the trial. The proportion of SU-sired lambs during Y2 which had been dewormed always remained higher with significant differences associated with KT comparisons. However, the lack of anthelmintic efficacy must be considered in analysis of deworming data. Multiple treatments may have resulted from the inability of the anthelmintic to clear GIN infection rather than the individual's ability to resist infection through immunity. The differential response to natural infection may have environmental as well as sire components. Variability between same breed sires for GIN resistance would result in fluctuations in environmental fitness and consequently changes in breed averages for resistance indicators. Selection of superior sires within breed may play an important role in the hardiness of lambs in a forage environment.

Despite the lack of differences between sire breeds for FEC and PCV, these resistance indicators were lowly to moderately related and were also related to FAMACHA scores. Further, ADG was associated with lnFEC and FAMACHA. Directions of all relationships were as expected with increases in lnFEC associated with greater FAMACHA scores and decreased PCV and ADG. The absence of a relationship between lnFEC or FAMACHA and ADG in SU-sired lambs should be evaluated further. lnFEC of SU- and TX-sired lambs were least volatile to changes in PCV possibly indicating a greater disconnect between these measures in these breeds. Regression coefficients for explanatory variables and ADG in SU-sired lambs were near zero (lnFEC: -0.02, FAMACHA: -0.01, PCV: -0.01); however no differences existed between the sire breeds. The reduced level of infection as indicated by FEC at the time of anthelmintic treatment may be a contributing factor. When all lambs were included in the dataset (including those treated with anthelmintics; Table 11b), similar trends persisted. Overall and within the TX-sired lambs, ADG tended to be related to PCV (r = 0.07, $P = 0.10$ and r = 0.12, $P = 0.10$; respectively). There were also sire breed effects on regression coefficients for PCV by lnFEC ($P < 0.05$) and the inverse ($P < 0.001$; Table 12b). In both regressions, KT-sired lambs were most sensitive to changes in PCV and lnFEC. No differences existed between the terminal sire breeds. These relationships confirm the ability to utilize PCV as an effective indicator of FEC changes in KT sheep and the inverse. However, economic relationships between PCV and FEC must be considered. In SU- and TX- sired lambs, the reduced variation in PCV/lnFEC as a result of changes in lnFEC/PCV make utilization of these indicators more challenging. However, correlations remain significant between lnFEC, PCV and FAMACHA score across breeds.

Kozaruk et al. (2015) reported a decrease in FECRT for rams and wethers compared to ewes suggesting an enhanced level of resistance in females. The authors here attributed this difference to inaccurate dosage BW estimation and selection criteria between male and female lambs. Further evidence by Abuargob and Stear (2014), suggests greater *T. cicumcincta* infections in ram lambs compared to ewe lambs with a greater associated immune response in ewe lambs. *H. contortus* infection is also greater in male lambs than ewes associated with greater FEC (Adams, 1989) and PCV (Colglazier et al., 1968). The tendency for ram lambs to have greater FEC and FAMACHA scores and lower PCV while requiring additional deworming supports the results observed previously. Further, trends suggested that ram lambs took fewer days before requiring deworming when anthelmintic treatment was administered at a baseline FAMACHA score. BW measured concurrently with deworming ensured correct anthelmintic dosages. Therefore, a potential physiologic mechanism may be responsible for this difference.

The immunosuppressive properties of androgens (testosterone) may result in the greater susceptibility of ram lambs to infection (Barger, 1993; Schuurs and Verheul, 1990). In females, greater estrogens levels have positive effects on immune function (humoral and cell mediated immunity) resulting in improved fitness during parasite infection (Schuurs and Verheul, 1990). Furthermore, greater levels of antinuclear antibodies were found in Soay sheep females. These antinuclear antibodies had a positive relationship with antibodies associated with *T. circumcincta* infection (Graham et al., 2010). Given ewes constitute the majority of sheep flocks, application of these results would have the greatest impact on forage finishing lamb enterprises grazing both male and female lambs.

Post grazing performance: BW and ADG

In Y1, sire breed and time influenced post grazing BW ($P < 0.001$; Table 13). There was an interaction of sire breed and time ($P < 0.001$). At the start of the post grazing period, TX-sired were the heaviest ($P < 0.01$) and SU-sired lambs had greater BW than KT-sired lambs ($P < 0.01$). After four weeks post grazing, TX- and SU-sired lambs remained heavier than KT-sired lambs ($P < 0.05$) with no differences between TX- and SU-sired lambs. At the end of the post grazing period, SU-sired lambs were heavier than KT-sired lambs ($P < 0.01$) with TX-sired lambs intermediate and not different from KT- or SU-sired lambs. Additionally, sex affected lamb BW during this period ($P < 0.01$) with an interaction of sex and time ($P < 0.05$). Ram lambs had greater BW than ewe lambs ($P < 0.05$) with a tendency at the mid time points of the post grazing period ($P = 0.09$). When breed, sex and time were fitted in the model along with their interactions, breed, sex and time all influenced lamb weight ($P < 0.001$). Interactions existed between breed and time ($P < 0.001$), sex and time ($P < 0.01$) and the three way interaction of breed, sex and time ($P < 0.001$).

Sire breed and time affected ADG of lambs over the post grazing period ($P < 0.05$; Table 13). There was no interaction of breed and time. No differences existed between sire breeds for ADG until the final measurement interval. At this point, SU-sired lambs had greater ADG than TX-sired lambs ($P < 0.01$) and tended to grow faster than KT-sired lambs ($P = 0.06$). Sex tended to influence ADG ($P = 0.09$) with an interaction of sex and time ($P < 0.01$). Ram lambs had greater ADG at the midpoint and final intervals of the post grazing period ($P < 0.05$) with no ADG differences at other intervals. When breed, sex and time were included in the model along with their interactions, breed, sex and time influenced ADG ($P < 0.05$). In addition, there were interactions of sex and time ($P < 0.001$), breed and sex ($P < 0.05$) and there tended to be an interaction between breed and time ($P = 0.08$). Overall, no differences existed between sire breeds for ADG during the post grazing period; however, ram lambs had greater ADG than ewe lambs ($P < 0.05$).

In Y2, sire breed affected post grazing BW ($P < 0.05$) and BW varied over time ($P < 0.001$; Table 13). There tended to be an interaction of breed and time ($P = 0.07$). At the start of the post grazing period, no differences existed between sire breeds. After two weeks, SU-sired lambs had greater BW than KT- and TX-sired lambs ($P < 0.05$). At the conclusion of the post grazing period, SU-sired lambs were heavier than KT-sired lambs ($P < 0.05$) with TX-sired lambs intermediate. There was no effect of sex on BW during this period. When breed, sex and time were included in the model along with the two and three way interactions, breed and time influenced BW ($P < 0.05$). Additionally, there was an interaction of breed and time ($P < 0.05$).

Sire breed did not influenced ADG over the post grazing period (Table 13). ADG varied over time ($P < 0.001$) with no interaction of sire breed and time. During the first two weeks post grazing, SU-sired lambs had greater ADG than KT- and TX-sired lambs ($P < 0.05$) but no differences existed between sire breeds for ADG at other intervals. Sex did not influence ADG post grazing. When breed, sex and time were included in the model along with the two and three way interactions, only time affected ADG ($P < 0.001$) with no interactions. No differences existed between sire breeds or sex for overall ADG during the post grazing period.

The post grazing environment here more closely replicated previous studies with intensive post weaning systems (Ali et al., 2005b; Notter et al., 2012; Leymaster and Jenkins, 1993). In both years, SU-sired lambs had greatest BW at the conclusion of the post grazing period. In Y1 at the start of the post grazing period, TX-sired lambs were heaviest while in Y2 no differences existed between sire breeds at this point. This superior growth of SU-sired lambs in an intensive environment is consistently supported in previous literature (Ali et al., 2005b; Notter et al., 2012; Leymaster and Jenkins, 1993). This advantage in ADG is more clearly observed in this parasite free environment. Prior studies would suggest rams lambs having greater ADG than ewe lambs during this period prior to harvest (Latif and Owen, 1979) as seen in Y1. The absence of differences in Y2 for ADG between sexes may have resulted from insufficient animal numbers as ram lambs had numerically greater gains.

Carcass Differences

In Y1, LW at the time of harvest were greater for SU-sired lambs than KT-sired lambs ($P < 0.05$; Table 14) with TX-sired lambs intermediate. HCW followed a similar trend with SU-sired lambs having greater HCW than KT-sired lambs ($P < 0.05$) and TX-sired lambs intermediate. No differences existed in FT or BWT. Sire breed tended to influence LMA ($P = 0.05$) with TX-sired lambs having greater LMA than KT-sired lambs ($P < 0.05$). KT-sired lambs had reduced LS compared to both SU- and TX-sired lambs ($P < 0.05$).

Ram lambs were heavier prior to harvest than ewe lambs ($P < 0.01$; Table 5) and had greater HCW ($P < 0.05$). Ram lambs had reduced FT ($P < 0.001$) and BWT ($P < 0.05$). Consequently, ADJFT and YG were lower for ram lambs ($P < 0.001$). Ewe lambs had greater KPH and FS ($P < 0.05$). LMA was greater for ram lambs ($P < 0.05$).

When breed and sex along with their interaction were included in the model, LW at harvest were lightest for KT-sired lambs ($P < 0.05$) and ewe lambs ($P < 0.001$) with no interaction. Additionally, HCW were lighter for KT-sired lambs than SU-sired lambs ($P < 0.01$) and tended to be lighter compared to TX-sired lambs ($P = 0.052$) with ewe lamb carcasses remaining the lightest ($P < 0.01$). FT was less for ram lambs ($P < 0.001$) and there was an interaction of breed and sex ($P < 0.05$). Ram lambs tended to have less BWT ($P = 0.06$). ADJFT was less for ram lambs ($P < 0.01$) along with KPH ($P < 0.05$). TX-sired lambs tended to have less internal fat compared to KT-sired lamb ($P = 0.06$). TX-sired lambs had greater LMA than KT-sired lambs ($P < 0.01$) and ram lambs had greater LMA than ewes ($P < 0.01$). Their tended to be an interaction between breed and sex for LMA ($P = 0.06$). LS was smallest for KT-sired lambs ($P < 0.01$). FS was greater for ewe lambs ($P < 0.05$) and ewe lambs tended to have greater QG ($P = 0.09$).

Live weight at harvest was highly correlated with HCW ($r = 0.88$, $P < 0.001$). LW had a moderate negative correlation with FT ($r = -0.57$, $P < 0.05$). Additionally, LW was highly correlated with LMA ($r = 0.71$, $P < 0.01$) and moderately correlated with LS ($r = 0.56$, $P < 0.05$). FT was moderately correlated with KPH ($r = 0.47$, $P < 0.05$), BWT ($r = 0.63$, $P < 0.01$), and FS ($r =0.47$, $P = 0.06$).

Year 2 harvest BW were greatest for SU-sired lambs ($P < 0.05$; Table 14). HCW did not differ between the sire breeds and there were also no differences in DP. LMA was greater for

TX-sired lambs compared to KT-sired lambs (*P* < 0.01). LS was smaller for KT-sired lambs than SU- and TX-sired lambs (*P* < 0.01). There were no differences in FT or BWT and consequently no differences in ADJFT and YG. Percentage of BCTRC did not differ. No differences existed between sire breeds for QG. Carcass primal percentages were similar among sire breeds. KT-sired lambs tended to have a greater percentage of loin compared to TX-sired lambs (*P* = 0.09). Carcass value resulting from composition did not differ between the sire breeds.

Sex of the lamb had no effect on live or HCW with no consequent differences in DP (Table 5). Ram lambs had reduced FT (*P* < 0.01) and BWT compared to ewe lambs (*P* < 0.01). ADJFT and YG were reduced for ram lambs (*P* < 0.01 and *P* < 0.01, respectively). Additionally, ram lambs had reduced KPH (*P* < 0.05). Ewe lambs had a greater FS than ram lambs (*P* < 0.05) and had a greater QG prior to conformation adjustment (*P* < 0.01). Ram lambs had a greater percentage of shoulder and non-HV cuts (*P* < 0.05 and *P* < 0.05; respectively). Ewe lambs had a greater percentage of leg (*P* < 0.05). Carcass value in terms of HV cuts tended to be greater for ewe lambs (*P* = 0.07); however, ram lambs had a greater percentage of BCTRC (*P* < 0.01).

When breed and sex along with the interaction of breed and sex where fixed in the model, sire breed affected LW prior to harvest (*P* < 0.05) with SU-sired lambs having the greatest BW. FT and BWT were reduced for ram lambs (*P* < 0.05). Consequently, ADJFT and YG were also lower for ram lambs (*P* < 0.01). LMA and LS was greater for TX-sired lambs than KT-sired lambs (*P* < 0.05). LMA tended to be greater for SU-sired lambs than KT-sired lambs (*P* = 0.07) and LS was greater for the SU-sired lambs (*P* < 0.05). FS and QG were greater for ewe lambs (*P* < 0.05). Shoulder percentage tended to be greater for ram lambs (*P* = 0.08) and loin percentage tended to be greater for KT-sired lambs than TX-sired lambs (*P* = 0.07). Ewe lambs had a greater leg percentage (*P* < 0.05). Non-HV cuts were greater for TX-sired lambs than KT-sired lambs (*P*

< 0.01) and ram lambs compared to ewe lambs (*P* < 0.01) with a significant interaction (*P* < 0.05). Internal fat percentage was reduced for ram lambs (*P* < 0.05). Additionally, ewe lambs tended to have greater carcass value in terms of HV cuts (*P* = 0.06). The percentage of BCTRC was greater for ram lambs (*P* < 0.05).

LW at harvest and HCW were highly correlated (r = 0.88, *P* < 0.001). There was no correlation between LW and FT, BWT, ADJFT, or LMA. LS was moderately correlated with LW (r = 0.49, *P* < 0.05). LMA was negatively correlated with both rack and loin percentage (r = -0.46, *P* = 0.06 and r = -0.62, *P* < 0.01; respectively). FT and percentage of KPH were moderately correlated and approached significance (r = 0.44, *P* = 0.07). FT and BWT were highly correlated (r = 0.75, *P* < 0.001). FT correlation with FS approached a tendency (r = 0.40, *P* = 0.1004).

In both years, SU-sired lambs had the greatest BW at harvest as expected (Leymaster and Jenkins, 1993; Ali et al., 2005b; Mousel et al., 2012). The lighter BW observed in KT-sired lambs agreed with those of Shackelford et al. (2012). HCW followed a similar trend as LW in Y1 with no differences in DP in both years. It would be expected for SU-sired lambs to have greater HCW than TX-sired lambs (Leymaster and Jenkins, 1993; Ali et al., 2005b; Shackelford et al., 2012). Shackelford et al. (2012) observed advantages for terminal-sired lambs over KT-sired lambs for HCW. The lack of HCW differences in Y2 may be explained by insufficient numbers as HCW followed a similar trend as LW with no DP differences. No breed differences in HCW were observed by Mousel et al. (2012). In both years, no differences existed for FT or BWT measurements. Results from Shackelford et al. (2012), Mousel et al. (2012), Ellis et al. (1997), Wolf et al. (1980) support the findings here. Contrary, Leymaster and Jenkins (1993) observed differences in FT at 105 and 147 d with SU-sired lambs having reduced FT. Decrease

FT was also observed by Ali et al. (2005b). The greater frame size and later maturity pattern of SU sheep would suggest these results. The absence of difference could be due to the relatively light finishing weight of the lambs in this experiment and consequently the lack of substantial fat accumulation. Muscling characteristics favored the terminal sire breeds as expected (Shackelford et al., 2012). In general, TX-sired lambs had greater LMA than SU-sired lambs agreeing with results of Ali et al. (2005), Wolf et al. (1980) and More O'Farrell and Timon (1977a). Contrary, Mousel et al. (2012), Leymaster and Jenkins (1993), Ellis et al. (1997) and Kempster et al. (1987) observed no differences. Previous results from Shackelford et al. (2012) support the reduced LS found in KT-sired lambs. In general, TX-sired lambs are reported to have greater LS than SU-sired lambs (Leymaster and Jenkins, 1993; Shackelford et al., 2012). However, those differences did not exist here. Previous studies utilized TX rams of direct European breeding (Leymaster and Jenkins, 1993). Selection priorities may have resulted in superior muscle development. However, Shackelford et al. (2012) utilized TX rams from industry flocks and noted greater LS in TX-sired lambs. The similarities in LS in this study may be an effect of BW. SU-sired lambs had greater HCW and consequently may have had larger leg muscle development.

Early studies utilizing ram lambs indicate some differences in slaughter weights and HCW between lamb sexes with greater weights associated with ram lambs (Latif and Owen, 1979, 1980). No differences were observed in fat and conformation scores (Latif and Owen, 1979). In more recent literature, no differences were observed for all carcass traits between sexes (Ellis et al., 1997; Shackelford et al., 2012) with the exception of 4th sacral vertebrae fat thickness which was greater for SU-sired wethers than SU-sired ewe lambs (Shackelford et al., 2012). Physiologically, ram lambs would be expected to have reduced internal and external fat and greater LMA at the same BW as ewe lambs with wethers intermediate (Boggs et al., 2006). These physiological characteristics were observed here. The absence of differences in previous studies could be attributed to greater BW of male lambs (Shackelford et al., 2012; Latif and Owen, 1979).

More O'Ferrall and Timon (1977) observed correlations between HCW and LMA that agreed with our results in Y1. The inverse relationship of LW and FT is contrary to expectations. Since correlations were across sire breeds, greater BW in SU-sired lambs associated with greater frame size may have resulted in decreased FT. As expect, FT was associated with other fat measurements (Boggs et al., 2006). The negative correlation between LMA and rack and loin percentage is unclear. Greater LMA would be expected to increase rack and loin weights. The tendency for TX-sired lambs to have reduced loin percentage may have resulted from decreased carcass length. While unmeasured here, previous literature suggests shorter carcasses in TX-sired lambs compared to other breeds (Ali et al., 2005b; Leymaster and Jenkins, 1993). This shorter carcass length may have resulted in shorter cut lengths and consequently decreased proportions despite greater LMA.

Generally, slaughter weights and HCW favored SU-sired lambs. TX-sired lambs had greater LMA and terminal sired lambs excelled KT-sired lambs for LS. Fat differences were negligible. Respective to those HV cuts, no differences existed in carcass value. Previous literature suggests variation in significance for carcass traits. Consequently, sire selection within breed may be a determining factor for improving lamb quality.

CONCLUSIONS AND IMPLICATIONS

Terminal sires (SU- and TX-sires) improved weaning performance while not sacrificing lambing ease. Survivability did not differ between sire breeds. Results from Y1 suggested that TX-sired lambs may have had growth advantages during the grazing season; however, no differences existed in Y2. While there were no sire breed effects on FEC or PCV, lower FAMACHA scores and consequently decreased frequencies of deworming favored the KT-sired lambs. Of the terminal sired lambs, TX-sired lambs tended to be more similar to KT lambs for GIN resistance. However, anthelmintic efficacy must be considered in grazing performance and GIN resistance measures as treatments did not clear GIN infection. Post-grazing, the intensive management system favored the SU-sired lambs. At harvest, lambs sired by SU rams had the greatest live and carcass weights. TX-sired lambs had greater LMA with no external fat differences between sire breeds. Potential exists for TX sires to improve growth performance while increasing muscling in slaughter lambs from hair sheep ewe flocks without significantly impacting parasite resistance. While post weaning performance favored SU-sired lambs, their decreased resistance and greater deworming requirements could be detrimental to their adaptability in extensive production systems. Within-breed variability in growth and parasite resistance may amplify the importance of individual sire selection as a determining factor in lamb performance.

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Chapter III: Potential areas of future research

Andrew R. Weaver

Clearly, the impact of GIN on sheep production is significant, especially in the southeastern U.S. Work here has demonstrated the ability to improve growth and carcass characteristics of KT lambs through terminal crossbreeding systems. KT-sired lambs remained superior in resistance traits; however, sire selection within the TX breed may allow for production of lambs with better resistance characteristics than SU-sired lambs. Further attention is needed in the identification of superior sires. Since the National Sheep Improvement Program began incorporating FEC data into their genetic evaluations, the KT breed has quickly adopted this technology and has seen significant reductions in breed FEC averages. Terminal sire breeds are beginning to utilize this tool. Additional data from SU and TX flocks would improve the accuracy of resistance selection in terminal sires as well as provide producers with additional sources of seedstock.

Post-weaning, ADG of lambs in this study was approximately half that of pre-weaning values. Average weaning age was between 70 and 80 d. At the time of weaning, no BCS concerns associated with lactation existed in the ewe flock. Therefore, additional days prior to weaning may provide additional growth in lambs while not negatively affecting ewe health and performance. Management practices more similar to that of western range producers with weaning occurring at approximately 120 d of age may be possible in extensive forage-based production systems in the southeastern U.S. Based on outcomes here, the additional 40-60 d of suckling may produce an additional 5-10 kg of BW at weaning per lamb. Secondary effects on ewe health must be monitored. Adequate body condition must be maintained and length of natural lactation must be considered.

Additional investigation of sex-associated differences in resistance should be considered. Previous studies from Australia and Europe support the differences observed here. The increased susceptibility of male lambs to GIN infection compared to females may have impacts in forage-finishing systems. Co-grazing of ram or wether lambs with ewe lambs may result in additional exposure of ewe lambs to larvae. Further, male lambs may require additional monitoring for parasitic gastroenteritis. Currently, genetic evaluations adjust BW records for sex. Further statistical evaluation of sex differences in FEC could provide opportunities for sex adjustments to resistance indicators allowing for more accurate comparisons of ram and ewe lambs within breed.

Finally, as our understanding of GIN infection and resistance in sheep expands, applications to cattle must be considered. Previous work in Brazil has indicated moderate heritability for GIN egg and *Eimeria* counts in Nellore cattle (Passafaro et al., 2015). Genetic variability in FEC within *Bos taurus* breeds would be indicative of selection potential for reduced FEC. Cattle of tropical origin (Nellore) demonstrate respectively similar characteristics of resistance as sheep of Caribbean origin (St. Croix) with little requirement for anthelmintic treatment. Composite cattle with Nellore ancestry (Brahman) may have a biological response to infection which could be compared to that of the Katahdin. Resistance characteristics of *B. taurus* cattle are unclear. Evaluation of GIN burden in *B. taurus* cattle as compared to *B. indicus* cattle could useful bench marks for GIN resistance in cattle. In addition, FEC collection from purebred *B. taurus* cattle may provide initial data sets for genetic evaluation programs in cattle. With robust genomic evaluations already established, breeds such as the Angus, Simmental or

Hereford, may be able to more easily relate resistance phenotypes with genotypic differences. Establishment of quantitative genetic selection tools for cattle producers to improve GIN resistance in their herds could have significant impacts, especially in Southern regions.

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APPENDICES

Table 1. Numbers[1] within breed and sire[2] for pasture management group

			Birth		Grazing[3]		Post Grazing[4]		Harvest[5]
Sire Breed	Sires	Ewes	NLB	NLW	Start	End	Start	End	
Year 1									
Katahdin	3	23	40 (19/21)	38 (19/19)	38 (19/19)	36 (17/19)	15 (4/11)	12 (6/6)	6 (3/3)
Sire 1	-	10	14 (7/7)	14 (7/7)	14 (7/7)	14 (7/7)	5 (1/4)	4 (2/2)	2 (1/1)
Sire 2	-	7	14 (5/9)	12 (5/7)	12 (5/7)	11 (4/7)	5 (2/3)	3 (2/1)	2 (1/1)
Sire 3	-	6	12 (7/5)	12 (7/5)	12 (7/5)	11 (6/5)	5 (1/4)	5 (2/3)	2 (1/1)
Suffolk	1	11	24 (9/14)[6]	20 (8/12)	20 (8/12)	20 (8/12)	10 (4/6)	9 (4/5)	6 (3/3)
Texel	1	12	23 (13/9)[6]	22 (13/9)	22 (13/9)	22 (13/9)	11 (5/6)	11 (5/6)	6 (3/3)
Year 2									
Katahdin	2	35	67 (42/25)	64 (42/22)	58 (36/22)	55 (33/22)	15 (7/8)	15 (7/8)	6 (3/3)
Sire 1	-	17	34 (23/11)	33 (23/10)	30 (20/10)	29 (19/10)	8 (4/4)	8 (4/4)	3 (2/1)
Sire 4	-	18	33 (19/14)	31 (19/12)	28 (16/12)	26 (14/12)	7 (3/4)	7 (3/4)	3 (1/2)
Suffolk	2	12	23 (8/15)	22 (7/15)	22 (7/15)	20 (6/14)	14 (5/9)	14 (5/9)	6 (3/3)
Sire 2	-	7	12 (4/8)	12 (4/8)	12 (4/8)	10 (3/7)	6 (2/4)	6 (2/4)	3 (1/2)
Sire 3	-	5	11 (4/7)	10 (3/7)	10 (3/7)	10 (3/7)	8 (3/5)	8 (3/5)	3 (2/1)
Texel	2	15	34 (20/14)	32 (19/13)	32 (19/13)	32 (19/13)	15 (10/5)	15 (10/5)	6 (3/3)
Sire 2	-	7	16 (9/7)	15 (9/6)	15 (9/6)	15 (9/6)	8 (5/3)	8 (5/3)	3 (2/1)
Sire 3	-	8	18 (11/7)	17 (10/7)	17 (10/7)	17 (10/7)	7 (5/2)	7 (5/2)	3 (1/2)

[1] Total (rams/ewes).

[2] Sires randomly selected from industry flocks. Over 2 years, a total of four Katahdin, three Suffolk and three Texel sires were utilized. One Katahdin sire was utilized in both year 1 and 2.

[3] Differences between NLW and grazing start can be attributed to those selected for ram test evaluation.

[4] Lambs selected for post grazing evaluation were within one standard deviation of mean weight at conclusion of grazing given equal sire representation.

[5] Lambs selected for harvest were within one standard deviation of mean weight at conclusion of post grazing given equal sex and sire representation.

[6] No sex recorded on stillborn lamb.

Table 2a. BW measurement periods[1]

	Date[2]	
Period	Year 1	Year 2
Avg Birth	26-Mar	18-Mar
Weaning	4-Jun	7-Jun
Grazing		
1	4-Jun	7-Jun
2	7-Jul	21-Jun
3	22-Jul	5-Jul
4	4-Aug	19-Jul
5	31-Aug[3]	2-Aug
6	-	16-Aug
7	-	30-Aug
P-Grazing		
1	31-Aug	30-Aug
2	5-Oct	12-Oct
3	28-Oct	4-Nov
4	5-Dec	28-Nov
5	6-Jan	-
6	18-Feb	-
Harvest	24-Feb	1-Dec

[1] Periods subdivided by grazing trial, post grazing (P-grazing), and harvest

[2] Year 1 (2015), Year 2 (2016)

[3] Time 5 FAMACHA score measurement occurred on 17-Aug

Table 2b. ADG measurement periods[1]

	Date[2]			
	Year 1		Year 2	
Period	Start	End	Start	End
Grazing				
1	4-Jun	7-Jul	7-Jun	21-Jun
2	7-Jul	22-Jul	21-Jun	5-Jul
3	22-Jul	4-Aug	5-Jul	19-Jul
4	4-Aug	31-Aug	19-Jul	2-Aug
5	-	-	2-Aug	16-Aug
6	-	-	16-Aug	30-Aug
P-Grazing				
1	31-Aug	5-Oct	30-Aug	12-Oct
2	5-Oct	28-Oct	12-Oct	4-Nov
3	28-Oct	5-Dec	4-Nov	28-Nov
4	5-Dec	6-Jan	-	-
5	6-Jan	18-Feb	-	-

[1] Periods subdivided by grazing trial and post grazing (P-grazing)

[2] Year 1 (2015), Year 2 (2016)

Table 3. Description of BW means for breed and sire[1] by period[2]

	Grazing Selection		Post Grazing Selection		Harvest Selection	
Sire Breed	Weaning Weight (kg)	Grazing Trial Start (kg)	Grazing Trial End (kg)	Post Grazing Start (kg)	Post Grazing End (kg)	Harvest Group (kg)
Year 1						
Katahdin	23.3	23.3	29.2	27.8	49.4	51.7
Sire 1	25.0	25.0	31.3	28.4	49.1	52.5
Sire 2	21.7	21.7	26.2	27.0	51.8	49.5
Sire 3	22.9	22.9	29.5	28.1	48.2	53.2
Suffolk	25.0	25.0	30.8	31.4	59.0	59.5
Texel	27.1	27.1	35.1	34.8	54.7	55.5
Year 2						
Katahdin	22.2	21.7	30.3	30.7	47.5	46.9
Sire 1	22.5	22.2	31.3	31.0	48.0	47.1
Sire 4	21.8	21.1	29.2	30.3	47.0	46.7
Suffolk	24.1	24.1	31.8	32.6	52.0	52.8
Sire 2	25.3	25.3	34.6	34.5	53.8	55.9
Sire 3	22.6	22.6	29.0	31.1	50.7	49.7
Texel	22.2	22.2	30.5	30.1	48.5	47.4
Sire 2	22.2	22.2	31.3	30.5	46.7	46.5
Sire 3	22.2	22.2	29.8	29.7	50.6	48.2

[1] Sires randomly selected from industry flocks. Over 2 years, a total of four Katahdin, three Suffolk and three Texel sires were utilized. One Katahdin sire was utilized in both year 1 and 2.

[2] Subset selection at the start of grazing, post grazing and harvest.

Table 4. Least-squares means of birth and growth performance for breed[1] and year[2]

	Year 1					Year 2				
Trait[3]	Katahdin	Suffolk	Texel	SEM[4]	*P*-value[5]	Katahdin	Suffolk	Texel	SEM[4]	*P*-value[5]
Ewe Age	5.86	5.45	4.42	-	-	4.4	4.7	4.9	-	-
Ewe[6], per head										
NLB	1.82	2.18	1.92	0.164	0.285	1.91	1.92	2.27	0.141	0.142
NLW	1.73	1.82	1.83	0.164	0.862	1.83	1.83	2.13	0.147	0.259
ADJNLB[7]	1.92	2.28	2.02	0.173	0.318	2.14	2.04	2.48	0.151	0.145
ADJNLW[7]	1.82	1.90	1.94	0.171	0.877	2.04	1.94	2.34	0.156	0.236
LL	0.09	0.36	0.08	0.112	0.175	0.09	0.08	0.13	0.072	0.865
ADJLL[7]	0.10	0.39	0.09	0.118	0.174	0.10	0.10	0.14	0.081	0.922
Lamb[8], BW, kg										
BT	4.3	4.4	4.3	0.148	0.889	4.1^{a}	4.7^{b}	4.1^{a}	0.107	0.002
ADJBT[9]	4.8	5.2	4.8	0.144	0.144	4.8^{a}	5.5^{b}	4.9^{a}	0.123	0.001
WWT	23.3^{a}	25.0^{ab}	27.1^{b}	0.928	0.013	22.2	24.1	22.2	0.747	0.183
ADJWWT[10]	23.6^{a}	25.7^{b}	26.8^{b}	0.568	0.0001	20.3^{a}	22.7^{b}	21.9^{b}	0.503	0.002
PWWT	29.2^{a}	30.8^{a}	35.1^{b}	1.166	0.0015	30.3	31.8	30.5	0.850	0.479
ADJPWWT[11]	33.5^{a}	36.1^{ab}	40.0^{b}	1.107	0.0002	34.3	36.5	35.9	0.843	0.145
WADG[12]	0.28^{a}	0.29^{ab}	0.32^{b}	0.011	0.010	0.22	0.24	0.23	0.008	0.136
ADJWADG[13]	0.31^{a}	0.34^{b}	0.37^{b}	0.008	< 0.001	0.26^{a}	0.29^{b}	0.28^{ab}	0.008	0.013
PADG[12]	0.06^{a}	0.07^{ab}	0.09^{b}	0.008	0.029	0.09	0.09	0.10	0.012	0.665
ADJPADG[14]	0.09^{a}	0.10^{ab}	0.13^{b}	0.008	0.009	0.12	0.13	0.13	0.010	0.613

[a,b] Means within a row with different superscripts differ ($P < 0.05$).

[1] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[2] Year represents date of birth, Year 1 (2015) or Year 2 (2016).

[3] Number of lambs born (NLB), number of lambs weaned (NLW), lamb Loss (LL), birth weight (BT), weaning weight (WWT), post-weaning weight (PWWT), pre-weaning ADG (WADG), post-weaning ADG (PADG).

[4] Average standard error of least square means.

[5] Test of sire breed effects within year.

[6] Traits evaluated on a per ewe basis with least square means per head.

[7] Adjusted for ewe age.

[8] Traits evaluated on a per lambs basis.

[9] Adjusted for NLB, sex and ewe age.

[10] Adjusted to 60-d of age for NLB, NLW, sex and ewe age.

[11] Adjusted to 165-d of age for sex, NLB, NLW and ewe age.

[12] ADG expressed as kg per d.

[13] Difference between ADJWWT and ADJBT over pre-weaning period. ADG expressed as kg per d.

[14] Differences between Adj Post Weaning and Adj Weaning BW over post weaning period. ADG expressed as kg per d.

Table 5. Least-squares means of growth and carcass characteristics for sex[1] and year[2]

	Year 1				Year 2			
Trait[3]	Ram	Ewe	SEM[4]	*P*-value[5]	Ram	Ewe	SEM[4]	*P*-value[5]
BW, kg								
BT	4.5[a]	4.2[b]	0.113	0.016	4.1[a]	4.4[b]	0.084	0.017
ADJBT[6]	4.8	5.0	0.115	0.408	4.7[a]	5.3[b]	0.090	< 0.0001
WWT	27.0[a]	22.6[b]	0.689	< 0.0001	22.4	22.7	0.577	0.762
ADJWWT[7]	25.4	24.6	0.497	0.247	20.6[a]	22.1[b]	0.392	0.007
PWWT	34.4[a]	28.3[b]	0.877	< 0.0001	31.5[a]	29.6[b]	0.643	0.047
ADJPWWT[8]	37.2*	34.8*	0.961	0.075	35.3	35.1	0.657	0.899
ADG, kg per d								
WADG	0.32[a]	0.27[b]	0.008	< 0.0001	0.23	0.23	0.007	0.748
ADJWADG[9]	0.34	0.33	0.007	0.145	0.26	0.28	0.006	0.110
PADG	0.08	0.07	0.006	0.125	0.10	0.08	0.010	0.185
ADJPADG[10]	0.11	0.10	0.007	0.129	0.13	0.12	0.008	0.564
LS[11], kg	54.9[a]	46.0[b]	1.93	0.005	46.7	47.7	1.24	0.571
HCW, kg	26.3[a]	22.5[b]	1.10	0.027	21.8	21.9	0.96	0.945
DP	47.7	49.0	1.21	0.449	46.5	45.8	1.08	0.631
ADJFT[12], cm	0.29[a]	0.48[b]	0.033	0.001	0.36[a]	0.55[b]	0.036	0.002
LMA, cm^2	17.3[a]	13.5[b]	1.01	0.017	15.3	14.6	0.52	0.368
LS[13]	11.6	11.4	0.47	0.871	10.8	10.8	0.22	1.000
KPH[14]	0.71[a]	1.09[b]	0.118	0.038	2.49[a]	3.57[b]	0.256	0.009
YG[15]	1.5[a]	2.3[b]	0.13	0.001	1.8[a]	2.6[b]	0.14	0.002
QG[16]	11.3	12.1	0.34	0.123	11.6	11.8	0.20	0.444
BCTRC[17]	49.3[a]	47.7[b]	0.37	0.007	49.0[a]	47.9[b]	0.25	0.007

[a,b] Means within a row with different superscripts differ ($P < 0.05$).

* Means within a row with asterisk tend to differ ($P < 0.10$).

[1] Effects of sex across sire breed. Sire breeds included purebred Katahdin, Suffolk and Texel sheep.

[2] Year represents date of birth, Year 1 (2015) or Year 2 (2016).

[3] Birth weight (BT), weaning weight (WWT), post-weaning weight (PWWT), pre-weaning ADG (WADG), post-weaning ADG (PADG), live weight (LW), dressing percentage (DP), 12th rib fat (FT), LM area (LMA), leg score (LS), Yield Grade (YG), Quality Grade (QG).

[4] Average standard error of least square means.

[5] Test of sex effects within year.

[6] Adjusted for sex, NLB and ewe age

[7] Adjusted to 60-d of age by sex, NLB, NLW and ewe age.

[8] Adjusted to 165-d of age for sex, NLB, NLW and ewe age.

[9] Difference between Adj Weaning and Adj Birth BW over pre-weaning period.

[10] Differences between Adj Post Weaning and Adj Weaning BW over post weaning period.

[11] BW immediately prior to harvest.

[12] Body wall adjusted rib fat: ADJFT = [((1/2)*Body Wall - 0.3556) + FT]/2.

[13] Conformation based on Average Choice = 11.

[14] Kidney, pelvic and heart fat expressed as a percentage of HCW.

[15] Yield grade calculated based on adjRF: YG = 3.94*ADJFT + 0.4.

[16] QG based on flank score, age and conformation.

[17] Percentage of boneless, closely trimmed retail cuts: BCTRC = 49.936 - (0.1866*HCW) - (1.723*FT) - (1.39*BWT) + (0.3807*LMA).

Table 6. Least-squares means of BW and ADG for breed[1] and time[2] during the grazing trial

			Time^{2}				
Year^{3} X Trait	1	2	3	4	5	6	Final^{4}
Year 1							
BW^{5,6}, kg							
Katahdin	23.3^{a}	26.0^{a}	29.0^{a}	28.6^{a}	-	-	29.2^{a}
Suffolk	25.0^{ab}	27.4^{ab}	30.7^{ab}	31.0^{ab*}	-	-	30.8^{a}
Texel	27.1^{b}	30.6^{b}	34.4^{b}	34.7^{b*}	-	-	35.1^{b}
SEM^{11}	0.93	1.04	1.17	1.15	-	-	1.17
P-value	0.013	0.006	0.005	0.001	-	-	0.002
ADG^{7}, kg per d							
Katahdin	0.06	0.22	-0.03	0.02	-	-	0.06^{a}
Suffolk	0.05	0.26	0.02	-0.01	-	-	0.07^{ab}
Texel	0.07	0.29	0.03	0.03	-	-	0.09^{b}
SEM^{11}	0.008	0.029	0.027	0.021	-	-	0.008
P-value	0.172	0.174	0.224	0.388	-	-	0.036
Year 2							
BW^{8,9}, kg							
Katahdin	21.7*	23.0^{a}	22.2^{a}	25.6^{a}	27.1^{a}	29.3*	30.3
Suffolk	24.1*	25.8^{b}	25.2^{b}	29.0^{b}	30.2^{b}	31.8*	31.8
Texel	22.2	23.6^{ab}	23.4^{ab}	26.6^{ab}	28.5^{ab}	29.8	30.5
SEM^{11}	0.74	0.73	0.71	0.74	0.74	0.79	0.85
P-value	0.080	0.042	0.015	0.009	0.013	0.092	0.479
ADG^{10}, kg per d							
Katahdin	0.10	-0.06^{a}	0.22*	0.10	0.17^{a}	0.07^{a}	0.10
Suffolk	0.08	-0.04^{ab}	0.27*	0.09*	0.13^{ab}	-0.01^{b}	0.09
Texel	0.10	-0.01^{b}	0.23	0.14*	0.09^{b}	0.05^{ab}	0.10
SEM^{11}	0.014	0.014	0.017	0.014	0.013	0.016	0.006
P-value	0.560	0.043	0.079	0.063	< 0.0001	0.007	0.239

[a,b] Means within a column with different superscripts differ ($P < 0.05$).

* Means within a column with asterisk tend to differ ($P < 0.10$).

[1] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[2] BW measurements taken at time points across grazing trial. See table 2 for time point and date relationships. Weight and ADG varied over time ($P < 0.0001$).

[3] Year 1 (2015), year 2 (2016).

[4] BW reflective of time 5 in Year 1 and time 7 in Year 2. ADG from beginning to end of the grazing trial. Calculated from BW at time 1 and time 5 (Year 1) or 7 (Year 2) over the respective number of grazing days.

[5] Sire breed effect ($P < 0.01$).

[6] Sire breed and time interaction ($P < 0.01$).

[7] Sire breed effect ($P = 0.06$).

[8] Sire breed effect ($P = 0.09$).

[9] Sire breed and time interaction ($P < 0.0001$).

[10] Sire breed and time interaction ($P < 0.0001$).

[11] Average standard error of least square means.

Table 7. Least-squares means of lnFEC, FAMACHA and PCV for breed[1], time[2] and year[3]

	Sire Breed														
	Katahdin			Suffolk			Texel			SEM[4]			*P*-value[5]		
Time[2]	lnFEC	FAMACHA	PCV	lnFEC	FAMACHA	PCV	lnFEC	FAMACHA	PCV	lnFEC	FAMACHA	PCV	lnFEC	FAMACHA	PCV
Year 1 [6,7]															
1	5.61	-	-	5.94	-	-	6.08	-	-	0.677	-	-	0.293	-	-
2	7.00	-	-	7.25	-	-	7.41	-	-	0.151	-	-	0.101	-	-
3	7.83	1.6^{a}	-	7.84	2.1^{ab}	-	8.08	2.4^{b}	-	0.152	0.18	-	0.415	0.003	-
4	6.90	1.3	-	7.11	1.5	-	7.06	1.6	-	0.240	0.21	-	0.767	0.537	-
5	7.63	1.7^{a}	-	7.70	2.7^{b}	-	7.59	1.8^{a}	-	0.322	0.24	-	0.980	0.005	-
Year 2 [8,9,10]															
1	6.93	1.2^{a}	34.7	7.01	1.4^{b}	34.0	6.89	1.0^{a}	35.5	0.212	0.07	0.67	0.939	0.004	0.354
2	7.19	1.2	31.0	7.28	1.5*	30.6	7.67	1.1*	30.5	0.191	0.09	0.79	0.114	0.056	0.825
3	7.25	1.7^{a}	30.1	6.96	2.0^{ab}	30.4	7.50	2.1^{b}	29.3	0.175	0.14	0.79	0.151	0.044	0.625
4	6.96	1.5	26.8	6.94	1.7	27.6	7.07	1.4	26.8	0.152	0.17	0.89	0.798	0.655	0.831
5	7.28	1.2	28.1	6.87	1.3	29.8	7.07	1.2	27.3	0.457	0.09	0.73	0.180	0.706	0.132
6	7.30	1.1	29.6	7.17	1.3	27.3	7.08	1.3	28.6	0.180	0.10	0.72	0.548	0.169	0.106
7	7.42	1.6	26.9	7.33	1.6	25.1	7.75	1.8	24.5	0.148	0.18	1.07	0.121	0.6224	0.132

[a,b] Means within a row with different superscripts differ ($P < 0.05$).

* Means within a row with asterisk tend to differ ($P < 0.10$).

[1] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[2] BW measurements taken at time points across grazing trial. See table 2 for time point and date relationships. lnFEC, FAMACHA and PCV varied over time ($P < 0.001$).

[3] Year 1 (2015), year 2 (2016).

[4] Average standard error of least square means.

[5] Test of sire breed effects within year.

[6] FAMACHA score varied by sire breed ($P < 0.05$).

[7] Sire breed and time interaction for FAMACHA score ($P < 0.05$).

[8] Sire breed and time interaction for lnFEC ($P = 0.09$).

[9] Sire breed tended to influence FAMACHA score ($P = 0.06$).

[10] Sire breed and time interaction for PCV ($P < 0.05$).

Table 8. Frequency[1] of anthelmintic treatments[2] for breed[3] and time[4]

	Year 1				Year 2			
	Katahdin	Suffolk	Texel	Chi sq[5]	Katahdin	Suffolk	Texel	Chi sq[5]
Number[6] of Treatments								
One	0.447 ± 0.081	0.700 ± 0.103	0.455 ± 0.106	0.1462	0.155 ± 0.048	0.182 ± 0.082	0.313 ± 0.082	0.2166
Two	0.184 ± 0.063	0.150 ± 0.080	0.091 ± 0.061	0.6021	0.138 ± 0.045	0.182 ± 0.082	0.156 ± 0.064	0.8868
Three	0.000	0.050 ± 0.049	0.136 ± 0.073	-	$0.017^{a} \pm 0.017$	$0.182^{b} \pm 0.082$	$0.031^{ab} \pm 0.031$	0.0313
Overall	0.632 ± 0.078	0.900 ± 0.067	0.682 ± 0.099	0.0658	0.310* ± 0.061	0.545* ± 0.106	0.500* ± 0.088	0.0762
Frequency by time[4]								
1	-	-	-	-	0.000	0.091 ± 0.061	0.000	-
2	-	-	-	-	0.034 ± 0.024	0.191 ± 0.086	0.000	-
3	$0.158^{a} \pm 0.059$	$0.350^{ab} \pm 0.107$	$0.545^{b} \pm 0.106$	0.0067	0.190 ± 0.051	0.429 ± 0.108	0.250 ± 0.077	0.1125
4	$0.270^{a} \pm 0.073$	$0.450^{ab} \pm 0.111$	$0.636^{b} \pm 0.103$	0.0200	0.250* ± 0.058	0.524* ± 0.109	0.313 ± 0.082	0.0804
5	0.649* ± 0.078	0.900* ± 0.067	0.682 ± 0.099	0.0837	0.250* ± 0.058	0.524* ± 0.109	0.313 ± 0.082	0.0804
6	-	-	-	-	0.255 ± 0.059	0.500 ± 0.112	0.344 ± 0.084	0.1380
7	-	-	-	-	0.309* ± 0.062	0.550* ± 0.112	0.500 ± 0.088	0.0807

[a,b] Means within a row with different superscripts differ ($P < 0.05$).

* Means within a row with asterisk tend to differ ($P < 0.10$).

[1] Results presented as frequency ± SEM. SEM and probability values unable to be determined when at least one breed = 0.

[2] Levamisole (8 mg/kg) or Moxidectin (0.2 mg/kg) were utilized for anthelmintic treatment.

[3] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[4] Anthelmintic treatment occurred at time points across grazing trial. See table 2 for time point and date relationships by year.

[5] Test of sire breed effects within year ($P >$ Chi sq).

[6] Per lamb basis cumulative over summer grazing trial.

Table 9. Least-squares means of lnFEC, FAMACHA and PCV for sex[1] and year[2]

	Ram			Ewe			SEM[3]			*P*-value[4]		
Time[5]	lnFEC	FAMACHA	PCV[6]	lnFEC	FAMACHA	PCV[6]	lnFEC	FAMACHA	PCV[6]	lnFEC	FAMACHA	PCV[6]
Year 1[7]												
1	5.96	-	-	5.73	-	-	0.183	-	-	0.365	-	-
2	7.22	-	-	7.11	-	-	0.120	-	-	0.550	-	-
3	8.01	2.08	-	7.80	1.78	-	0.120	0.150	-	0.220	0.160	-
4	7.36^{a}	1.63*	-	6.71^{b}	1.27*	-	0.168	0.151	-	0.008	0.099	-
5	8.01*	2.11	-	7.47*	1.86	-	0.212	0.200	-	0.096	0.378	-
Year 2[8,9,10]												
1	6.95	1.19	34.5	6.90	1.14	35.0	0.160	0.057	0.52	0.825	0.507	0.500
2	7.54^{a}	1.26	29.9^{a}	7.10^{b}	1.21	31.9^{b}	0.144	0.069	0.58	0.033	0.584	0.014
3	7.38	1.93	29.4	7.17	1.79	30.5	0.134	0.105	0.59	0.257	0.338	0.188
4	7.08	1.50	25.7^{a}	6.89	1.45	28.1^{b}	0.110	0.124	0.62	0.211	0.776	0.008
5	7.18	1.16	28.0	7.15	1.24	28.2	0.111	0.066	0.54	0.826	0.426	0.750
6	7.30	1.17	29.1	7.14	1.24	28.9	0.128	0.072	0.53	0.388	0.494	0.776
7	7.60	1.69	25.7	7.41	1.65	26.3	0.108	0.127	0.78	0.233	0.800	0.571

^{a,b} Means within a row with different superscripts differ ($P < 0.05$).

* Means within a row with asterisk tend to differ ($P < 0.10$).

[1] Effects of sex across sire breed. Sire breeds included purebred Katahdin, Suffolk and Texel sheep.

[2] Year represents date of birth, Year 1 (2015) or Year 2 (2016).

[3] Average standard error of least square means.

[4] Test of sex effects within year.

[5] Refer to table 2 for time point and date relationships. lnFEC, FAMACHA and PCV varied over time ($P < 0.001$).

[6] No packed cell volume measurements were recorded in year 1.

[7] lnFEC and FAMACHA score varied by sex ($P < 0.05$).

[8] Sex tended to influence lnFEC ($P = 0.07$).

[9] Sex tended to influence PCV ($P = 0.07$).

[10] Interaction of sex and time for PCV ($P < 0.05$).

Table 10. Least-squares means of days[1], lnFEC, PCV and FAMACHA at the time of first and second anthelmintic treatment[2] during Year 2 grazing trial

	Sire Breed					SEM[3]		*P*-Value[4]	
	Katahdin	Suffolk	Texel	Ram	Ewe	Breed	Sex	Breed	Sex
Days[1]									
First									
Year 1	73.7^{a}	65.0^{ab}	63.1^{b}	64.8^{a}	72.5^{b}	3.097	2.483	0.023	0.031
Year 2	38.9	28.0*	49.9*	37.7	43.6	6.113	5.309	0.063	0.433
Second									
Year 1	83.4	84.2	79.9	81.4	84.5	2.139	1.728	0.372	0.200
Year 2	66.9	59.5	81.7	69.2	65.3	7.396	7.049	0.151	0.712
Trait									
lnFEC	8.21^{a}	7.51^{b}	8.24^{a}	7.99	8.22	0.166	0.146	0.013	0.276
PCV	22.56	24.82	23.00	24.00	22.06	1.455	1.181	0.555	0.255
FAMACHA	3.3	3.0	3.1	3.1	3.1	0.101	0.087	0.124	0.871

[a,b] Means within a row with different superscripts differ ($P < 0.05$).

* Means within a row with asterisk tend to differ ($P < 0.10$).

[1] Days from the start of the grazing trial (Time 1) to first or second anthelmintic treatment.

[2] Anthelmintic treatment administered based on FAMACHA score ≥ 3.

[3] Average standard error of least square means.

[4] Test of sire breed effects within year.

Table 11a. Correlations[1] between parasite resistance indicators[2] and ADG[3] during the grazing trial for breed[4] excluding lambs treated[2] prior to measurement

Overall[5]	lnFEC	FAMACHA	PCV	ADG	Katahdin	lnFEC	FAMACHA	PCV	ADG
lnFEC	-	0.33	-0.52	-0.15	lnFEC	-	0.30	-0.58	-0.15
FAMACHA	< 0.0001	-	-0.46	-0.21	FAMACHA	< 0.0001	-	-0.46	-0.22
PCV	< 0.0001	< 0.0001	-	-0.01	PCV	< 0.0001	< 0.0001	-	0.01
ADG	0.0007	< 0.0001	0.87	-	ADG	0.01	0.0001	0.81	-
Suffolk	lnFEC	FAMACHA	PCV	ADG	Texel	lnFEC	FAMACHA	PCV	ADG
lnFEC	-	0.31	-0.46	-0.04	lnFEC	-	0.40	-0.45	-0.23
FAMACHA	0.003	-	-0.49	-0.02	FAMACHA	< 0.0001	-	-0.45	-0.30
PCV	< 0.0001	< 0.0001	-	-0.08	PCV	< 0.0001	< 0.0001	-	0.00
ADG	0.73	0.84	0.46	-	ADG	0.0045	0.0001	0.98	-

[1] Correlations and *P*-values are shown above and below the diagonal, respectively.

[2] Upon anthelmintic treatment, individual data for parasite resistance indicators removed from analysis. Only lambs not previously treated were included in correlation analysis.

[3] ADG for time period immediately proceeding parasite resistance indicator measurement utilized.

[4] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[5] Across breed correlations.

Table 11b. Correlations[1] between parasite resistance indicators[2] and ADG[3] during the grazing trial for breed[4] including all lambs[2]

Overall[5]	lnFEC	FAMACHA	PCV	ADG	Katahdin	lnFEC	FAMACHA	PCV	ADG
lnFEC	-	0.32	-0.48	-0.22	lnFEC	-	0.35	-0.58	-0.19
FAMACHA	< 0.0001	-	-0.53	-0.21	FAMACHA	< 0.0001	-	-0.54	-0.20
PCV	< 0.0001	< 0.0001	-	0.07	PCV	< 0.0001	< 0.0001	-	0.03
ADG	< 0.0001	< 0.0001	0.0975	-	ADG	0.0007	0.0003	0.54	-
Suffolk	lnFEC	FAMACHA	PCV	ADG	Texel	lnFEC	FAMACHA	PCV	ADG
lnFEC	-	0.22	-0.29	-0.25	lnFEC	-	0.39	-0.41	-0.31
FAMACHA	0.0132	-	-0.55	-0.13	FAMACHA	< 0.0001	-	-0.52	-0.32
PCV	0.0011	< 0.0001	-	0.08	PCV	< 0.0001	< 0.0001	-	0.12
ADG	0.0078	0.1358	0.39	-	ADG	< 0.0001	< 0.0001	0.10	-

[1] Correlations and *P*-values are shown above and below the diagonal, respectively.

[2] All lambs included in analysis regardless of anthelmintic treatment status.

[3] ADG for time period immediately proceeding parasite resistance indicator measurement utilized.

[4] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[5] Across breed correlations.

Table 12a. Regression coefficients of parasite resistance indicators[1] and ADG[2] over the grazing trial for breed[3] excluding lambs treated[1] prior to measurement

		Katahdin		Suffolk		Texel		Overall[4]		
Y	X	β_1	β_0	β_1	β_0	β_1	β_0	β_1	β_0	β_1 Significance[5]
lnFEC										
	FAMACHA	0.44	6.59	0.32	6.58	0.51	6.58	0.43	6.60	0.5142
	PCV	-0.11^{a}	10.56	-0.07^{b}	9.07	-0.08^{b}	9.55	-0.10	10.02	0.0064
	ADG	-0.54	7.34	-0.10	7.11	-0.79	7.55	-0.50	7.36	0.3106
FAMACHA										
	lnFEC	0.21	-0.12	0.30	-0.60	0.32	-0.89	0.24	-0.34	0.1992
	PCV	-0.06	3.16	-0.07	3.59	-0.06	3.22	-0.06	3.24	0.8374
	ADG	-0.56	1.50	-0.06	1.60	-0.92	1.70	-0.57	1.56	0.0574
PCV										
	lnFEC	-2.95	50.83	-3.20	52.11	-2.65	48.63	-2.88	50.23	0.6953
	FAMACHA	-3.47	34.54	-3.52	35.36	-3.33	34.11	-3.41	34.50	0.9627
	ADG	0.24	28.85	-1.37	29.06	0.03	28.09	-0.13	28.68	0.7314
ADG										
	lnFEC	-0.04	0.52	-0.02	0.29	-0.07	0.70	-0.05	0.53	0.5784
	FAMACHA	-0.09	0.32	-0.01	0.17	-0.10	0.36	-0.08	0.31	0.1583
	PCV	0.00	0.17	-0.01	0.31	0.00	0.20	0.00	0.21	0.7128

[a,b] β_1 within a row with different superscripts differ ($P < 0.05$).

[1] Upon anthelmintic treatment, individual data for parasite resistance indicators removed from analysis. Only lambs not previously treated were included in regression analysis.

[2] ADG for time period immediately proceeding parasite resistance indicator measurement utilized.

[3] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[4] Across breed results for β_1 and β_0.

[5] *P*-value for hypothesis test of differences between β_1 across sire breeds.

Table 12b. Regression coefficients of parasite resistance indicators[1] and ADG[2] over the grazing trial for breed[3] including all lambs[1]

		Katahdin		Suffolk		Texel		Overall[4]		
Y	X	β_1	β_0	β_1	β_0	β_1	β_0	β_1	β_0	β_1 Significance[5]
lnFEC										
	FAMACHA	0.45	6.58	0.24	6.6	0.49	6.51	0.4	6.59	0.1388
	PCV	-0.11^{a}	10.36	-0.05^{b}	8.42	-0.07^{b}	9.33	-0.09	9.68	0.0004
	ADG	-0.66	7.41	-0.71	7.16	-1.17	7.55	-0.78	7.40	0.2843
FAMACHA										
	lnFEC	0.27	-0.50	0.20	0.31	0.31	-0.73	0.26	-0.35	0.4808
	PCV	-0.08	3.67	-0.08	4.04	-0.07	3.57	-0.08	3.73	0.7877
	ADG	-0.55	1.59	-0.37	1.85	-1.04	1.78	-0.63	1.69	0.1019
PCV										
	lnFEC	-3.11^{a}	51.47	-1.71^{b}	40.49	-2.34^{b}	45.74	-2.63	47.77	0.0151
	FAMACHA	-3.83	34.69	-3.71	35.15	-3.71	34.35	-3.72	34.61	0.9640
	ADG	0.60	28.20	1.34	27.65	2.28	27.25	1.16	27.83	0.6331
ADG										
	lnFEC	-0.05	0.61	-0.09	0.81	-0.08	0.80	-0.06	0.69	0.4145
	FAMACHA	-0.07	0.32	-0.05	0.28	-0.10	0.37	-0.07	0.33	0.4074
	PCV	0.00	0.16	0.00	0.07	0.01	0.04	0.00	0.11	0.7048

[a,b] β_1 within a row with different superscripts differ ($P < 0.05$).

[1] Individual data for parasite resistance indicators utilized prior to and following anthelmintic treatment.

[2] ADG for time period immediately proceeding parasite resistance indicator measurement utilized.

[3] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[4] Across breed results for β_1 and β_0.

[5] *P*-value for hypothesis test of differences between β_1 across sire breeds.

Table 13. Least-squares means of BW and ADG for breed[1] and time[2] during the post grazing period

			Time[2]			
Year[3] X Trait	1	2	3	4	5	Final[4]
Year 1						
BW[5,6], kg						
Katahdin	27.8^{a}	29.6^{a}	33.2^{a}	37.7^{a}	37.7^{a}	49.4^{a}
Suffolk	31.4^{b}	33.6^{b}	37.0^{b}	42.1^{ab}	43.7^{b}	59.0^{b}
Texel	34.8^{c}	37.1^{b}	40.1^{b}	44.9^{b}	44.3^{b}	54.7^{ab}
SEM[10]	0.72	1.08	1.00	1.51	1.39	2.10
P-value	< 0.0001	< 0.0001	< 0.0001	0.005	0.002	0.012
ADG[7], kg per d						
Katahdin	0.05	0.13	0.13	0.00	0.27^{ab}	0.15
Suffolk	0.06	0.14	0.12	0.05	0.35^{a}	0.16
Texel	0.07	0.13	0.13	-0.02	0.24^{b}	0.12
SEM[10]	0.02	0.02	0.02	0.03	0.02	0.02
P-value	0.797	0.793	0.962	0.178	0.010	0.133
Year 2						
BW[8,9], kg						
Katahdin	30.7	40.8^{a}	45.0^{a}	-	-	47.5^{a}
Suffolk	32.6	45.0^{b}	49.0^{b}	-	-	52.0^{b}
Texel	30.1	40.9^{a}	45.5^{ab}	-	-	48.5^{ab}
SEM[10]	0.86	0.97	1.06	-	-	1.19
P-value	0.127	0.005	0.023	-	-	0.027
ADG, kg per d						
Katahdin	0.24^{a}	0.18	0.10	-	-	0.19
Suffolk	0.29^{b}	0.17	0.13	-	-	0.22
Texel	0.25^{a}	0.20	0.13	-	-	0.20
SEM[10]	0.010	0.017	0.022	-	-	0.01
P-value	0.001	0.455	0.702	-	-	0.139

[a,b,c] Means within a column with different superscripts differ ($P < 0.05$).

[1] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F_1 generation for evaluation.

[2] BW measurements taken at time points across post grazing period. See table 2 for time point and date relationships. BW and ADG varied by time ($P < 0.01$).

[3] Year 1 (2015), year 2 (2016).

[4] BW reflective of time 6 in Year 1 and time 4 in Year 2. ADG from beginning to end of the post grazing trial. Calculated from BW at time 1 and time 6 (Year 1) or 4 (Year 2) over the respective number of post grazing days.

[5] Sire breed and time interaction for BW ($P < 0.001$).

[6] Sire breed effect ($P < 0.001$).

[7] Sire breed effect ($P < 0.01$).

[8] Sire breed and time interaction ($P = 0.07$).

[9] Sire breed effect ($P < 0.05$).

[10] Average standard error of least square means.

Table 14. Least-squares means of carcass characteristics for breed[1] and year[2]

	Year 1					Year 2				
Trait[3]	Katahdin	Suffolk	Texel	SEM[4]	*P*-value[5]	Katahdin	Suffolk	Texel	SEM[4]	*P*-value[5]
LW[6], kg	44.9^{a}	54.7^{b}	51.7^{ab}	2.56	0.043	45.6^{a}	50.3^{b}	45.6^{a}	1.23	0.024
HCW, kg	21.5^{a}	26.7^{b}	24.9^{ab}	1.30	0.034	20.9	23.7	20.9	1.06	0.136
DP	48	49	48	1.55	0.871	45.7	46.9	45.9	1.35	0.809
FT, cm	0.36	0.39	0.35	0.064	0.887	0.42	0.38	0.49	0.069	0.559
BWT, cm	1.48	1.65	1.51	0.142	0.676	1.67	1.54	1.80	0.111	0.298
ADJFT[7], cm	0.37	0.43	0.37	0.061	0.749	0.45	0.40	0.52	0.058	0.383
KPH[8]	1.15*	0.87	0.68*	0.148	0.105	3.36	2.57	3.16	0.38	0.326
LMA, cm^2	13.0*	15.4	17.7*	1.25	0.050	13.5^{a}	15.2^{ab}	16.1^{b}	0.48	0.005
LS[9]	10.0^{a}	11.8^{b}	12.7^{b}	0.34	0.0002	10.2^{a}	11.2^{b}	11.0^{b}	0.20	0.007
FS[10]	434	338	344	40.0	0.187	373	398	375	25.5	0.745
YG[11]	1.9	2.1	1.9	0.24	0.749	2.2	2.0	2.4	0.23	0.383
QG[12]	11.5	11.8	11.8	0.47	0.852	11.3	12.0	11.7	0.23	0.152
BCTRC[13]	48.2	47.9	49.4	0.51	0.119	48.1	48.5	48.8	0.38	0.436
Shoulder[14]	-	-	-	-	-	20.2	20.3	19.6	0.75	0.765
Rack[14]	-	-	-	-	-	10.9	10.9	10.8	0.39	0.998
Loin[14]	-	-	-	-	-	9.8*	9.4	8.5*	0.41	0.097
Leg[14]	-	-	-	-	-	32.3	32.1	32.5	0.50	0.847
Other[15]	-	-	-	-	-	23.6*	24.8	25.6*	0.62	0.109
Value[16]	-	-	-	-	-	303	300	295	3.4	0.225

[a,b] Means within a row with different superscripts differ ($P < 0.05$).

* Means within a row with asterisk tend to differ ($P < 0.10$).

[1] Lambs sired by purebred Katahdin, Suffolk or Texel rams sourced from industry flocks. Sires were randomly paired with Katahdin ewes producing F$_1$ generation for evaluation.

[2] Year represents date of birth, Year 1 (2015) or Year 2 (2016).

[3] Live weight (LW), dressing percentage (DP), 12th rib fat (FT), body wall thickness (BWT), LM area (LMA), leg score (LS), flank score (FS), Yield Grade (YG), Quality Grade (QG), IMPS 207 (Shoulder), IMPS 204 (Rack), IMPS 232 (Loin), IMPS 233A (Leg).

[4] Average standard error of least square means.

[5] Test of sire breed effects within year.

[6] BW taken immedately prior to harvest.

[7] Body wall adjusted rib fat: ADJFT = [((1/2)*Body Wall - 0.3556) + FT]/2.

[8] Kidney, pelvic and heart fat (KPH) expressed as a percentage of HCW.

[9] Conformation based on Average Choice = 11.

[10] Flank scores based on Small^{0} = 300.

[11] Yield grade calculated based on adjRF: YG = 3.94*ADJFT + 0.4.

[12] QG based on flank score, age and conformation.

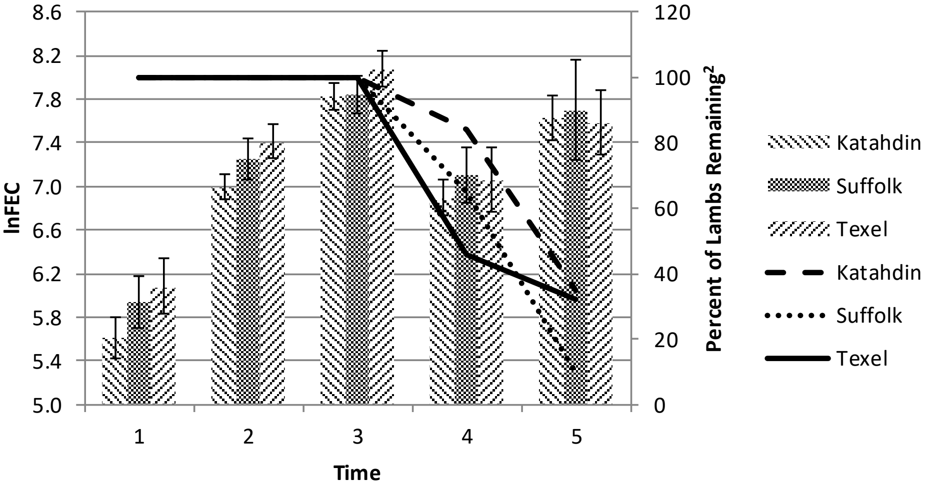
[13] Percentage of boneless, closely trimmed retail cuts: BCTRC = 49.936 - (0.1866*HCW) - (1.723*FT) - (1.39*BWT) + (0.3807*LMA).

[14] High value (HV) primal cuts expressed as a percentage of chilled carcass weight.

[15] Non-HV cuts expressed as a percentage of chilled carcass weight.

[16] Carcass value based on primal cut composition and value. Prices based on USDA Weekly National Lamb Market Summary; Dec. 2, 2016.

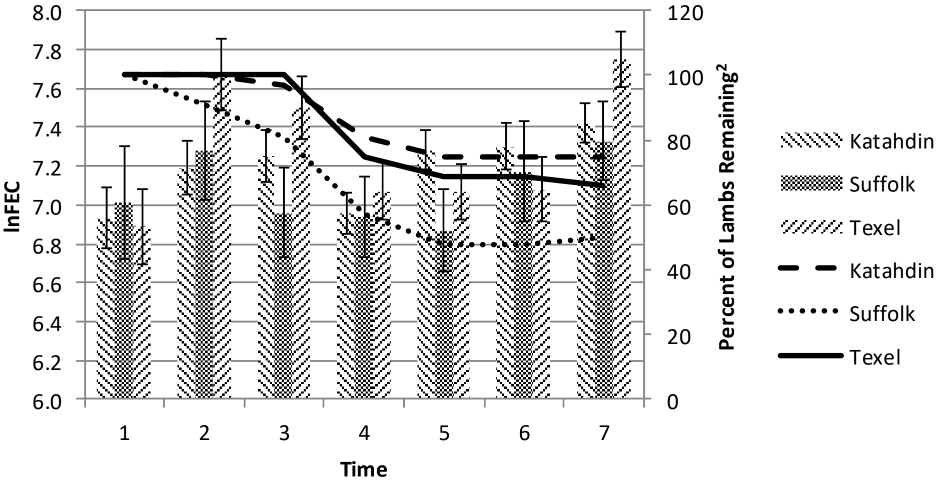
Figure 1a. lnFEC over time[1] during Year 1 grazing trial



[1] lnFECmeasurements taken at time points across grazing trial. See table 2 for time point and date relationships. lnFEC varied over time (P < 0.001).

[2] Lamb FEC data removed for remaining time points after treatment. Proportion of lambs not treated prior to that time point expressed as percentage of lambs remaining in the population.

Figure 1b. lnFEC over time[1] during Year 2 grazing trial



[1] lnFECmeasurements taken at time points across grazing trial. See table 2 for time point and date relationships. lnFEC varied over time (P < 0.001).

[2] Lamb FEC data removed for remaining time points after treatment. Proportion of lambs not treated prior to that time point expressed as percentage of lambs remaining in the population.