FACTORS AFFECTING GASTROINTESTINAL NEMATODE INFECTION IN GOATS

by

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LIST OF ABBREVIATIONS

Abbreviation	Description
AIC	Akaike information criterion
EPG	eggs per gram
FAMACHA	FAffa MAlan CHArt
FEC	fecal egg counts
FECRT	fecal egg count reduction test
NB	negative binomial
PCV	packed cell volume (also called hematocrit)
ZINB	zero-inflated negative binomial
ZIP	zero-inflated Poisson

ABSTRACT

Parasitic infections are one of the costliest concerns in animal production, with over $10 billion each year spent on medications globally. Internal parasites cause $18.2 million in sheep and goat losses annually in the United States alone. *Haemonchus contortus* is the primary parasitic nematode affecting Texas small ruminant production and contributes to substantial economic losses due to few clinical signs before death, reduced productivity, treatment costs, and is developing anthelmintic resistance worldwide. Small ruminants with anthelmintic resistant nematode infection sell for 14% less than lambs without resistant infections. Some alternatives to standard herd-wide anthelmintic dosing schedules that help mitigate anthelmintic resistance are frequent monitoring via fecal egg counts (FEC) and FAffa MAlan CHArt (FAMACHA), allowing self-medicating with bioactive plants, and determining which factors affect FEC. The proposed work hypothesizes that breed, age, and other factors will affect a goat's infection level. Previous work shows these factors affect a goat's FEC. There are two objectives to the proposed work: 1. to determine weekly FEC for 39 goats at Freeman Center for over 1-yr and 2. to determine relationships between assessed factors and FEC measures using regression analysis. The best fit model was zero-inflated negative binomial distribution due to aggregated parasite infections and the zero-frequency class being contaminated with samples that are not part of the infection process. The Spanish-Boer crossbred goats had the highest FEC of evaluated breeds ($P < 0.001$). January

through April were higher than the remaining months, which coincides with the *H. contortus* proliferation season ($P < 0.05$).

Keywords: breed, *Capra hircus*, fecal egg count, *Haemonchus contortus*, month, regression analysis

I. INTRODUCTION

Parasitic infections are a significant concern in animal agriculture. Producers spend over $10 billion each year to control parasitic infections worldwide. In animal production, parasitic nematodes cause substantial economic losses (Roeber et al., 2013). Internal parasites cause $18.2 million in sheep and goat losses yearly in the United States (USDA, 2015; USDA, 2017). In the recent USDA Needs Assessment Survey (2018), internal parasites were the number one disease concern of goat owners, veterinarians, and others, with 47.4% of participants listing it as their first concern.

Texas is the largest producer of goats in the United States, with nearly one-third of goats produced in the state alone (USDA, 2017). As a result, the economic impacts of internal parasites in Texas are substantial. The USDA (2017) estimated the goat production loss to nonpredators, including internal parasites, in Texas at 8.3%, worth over $8.2 million. In sheep, 4.3%, or $6.2 million, of Texas sheep were lost to nonpredators (USDA, 2015). These economic loss estimates do not include the resources used to raise the livestock that eventually dies from parasitic infection, nor the reduced meat, milk, and fiber produced from the infection.

Since the introduction of anthelmintics (colloquially referred to as dewormers) over 60-yrs ago, they have been the primary treatment method for all parasitic infections (Hoste and Torres-Acosta, 2011; Roeber et al., 2013). The use of anthelmintics as a primary treatment for *H. contortus* infections has resulted in the overexposure of the parasite to subtherapeutic doses of anthelmintics. This overexposure allowed nematodes with anthelmintic-resistant genes to reproduce more effectively than non-resistant nematodes (Prichard et al., 1980; Sargison, 2012). Thus, *H. contortus* has developed

resistance to commercial anthelmintics worldwide, increasing the economic impacts of reduced production and livestock death (Cai et al., 2017).

As *H. contortus* develops resistance, it is imperative to investigate alternatives to anthelmintic use. Some examples of alternatives to anthelmintics include fungi, bioactive plants, and vaccine development (Palacios-Landín et al., 2015; Cai et al., 2017; González-Sánchez et al., 2018). Another alternative to manage nematode infections is manipulating the factors which increase a goat's susceptibility to gastrointestinal nematode infection. This study hypothesized that several factors, including breed and age, affect a goat's gastrointestinal infection level.

II. LITERATURE REVIEW

Gastrointestinal Nematodes

Parasitic nematodes (colloquially referred to as worms) have evolved alongside their hosts, the organisms they infect. The parasites have developed ways to avoid detection and gain their required nutrients from their hosts yet allow their hosts to survive long enough for the parasites to reproduce (Sargison, 2012). Concomitantly, the hosts have enhanced their ability to detect and eradicate the parasite. The host and parasite continually change to improve their chance of survival (Hutchings et al., 2003). Gastrointestinal nematodes are the primary parasitic concern in small ruminant production due to productivity losses, cost of treatment, and livestock death (Greer, 2008; Roeber et al., 2013; Cai et al., 2017).

Parasite-Host Interactions

The interactions between individual parasites and their hosts significantly impact the host's infection level. Additionally, both interact with the environment and production methods to determine the severity of infection in an agricultural production herd. Figure 1 displays some of these interactions.

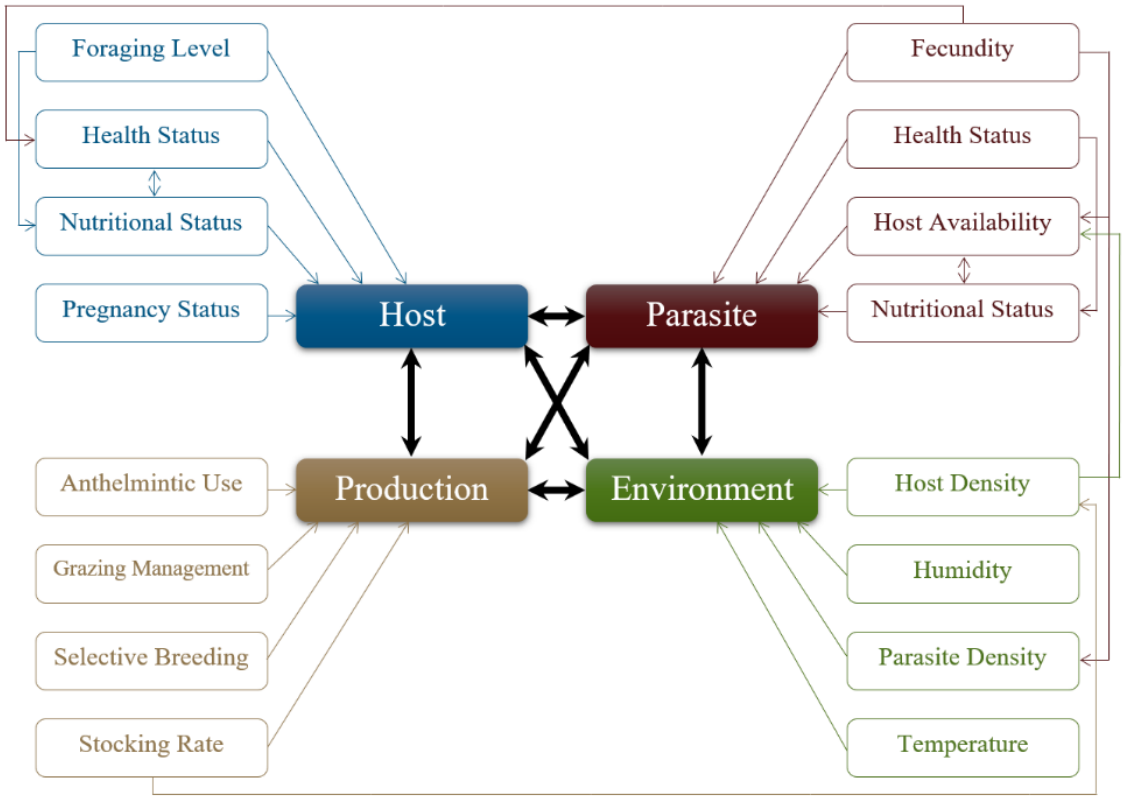

Figure 1. Host, Parasite, Production Methods, and Environment Interactions. This figure displays some of the interactions involved.
Sources: Sargison, 2012; Roeber et al., 2013

Any parasitic infection directly reduces nutrient availability because the parasite consumes the nutrients ingested by the host (Amit et al., 2013). Similarly, infections increase the host's immune response, diverting acquired nutrients to fight the infection. This immune response reduces the gain-to-feed ratio in livestock (Greer, 2008; Sargison, 2012). During one experiment, uninfected lambs gained a mean of 6.8-kg of BW while the infected animals gained only 0.2-kg, resulting in a reduction of expected weight gain by 97% (Abbott et al., 1986). Furthermore, infections can lead to electrolyte imbalances, protein deficiencies, and anemia, which further reduce the productivity of the animal and increase the chances of death due to infection (Abbott et al., 1986; Sargison, 2012).

Both parasite and host interactions with the environment affect the spread of the disease through the host herd. The local climate directly affects the propagation of a parasite species indigenous to the region. However, anthelmintic use and grazing management systems affect the species of parasites that survive in the environment (Sargison, 2012; Roeber et al., 2013).

As a result of these interactions, parasitic infections do not uniformly infect a herd. Parasite infections are aggregated, meaning they often overly infect a small proportion of a herd while minimally affecting the remaining animals. The frequency distribution of parasites per host due to this aggregation pattern is usually best described by the negative binomial (NB) distribution (Barger, 1985; Jones et al., 1991; Kaplan et al., 2004). A common rule of thumb is that 80% of the parasite population is in 20% of the hosts (Kaplan et al., 2004). Other factors affecting the severity of parasitic infections are the species and intensities of nematodes, the climate, the stocking rate, and the overall health and diet of the small ruminant (Roeber et al., 2013).

Haemonchus contortus

H. contortus is the primary parasitic nematode affecting Texas small ruminant production (Machen et al., 2017). However, it is found worldwide, especially in warm, humid areas. Globally, *H. contortus* accounts for 15% of all gastrointestinal diseases in small ruminants (González-Sánchez et al., 2018). It is also a significant cause of mortality (Emery et al., 2018). The mortality rate of *H. contortus* infection is partially due to a lack of apparent early warning signs, and caretakers usually do not know the host is sick until just before death (Kaplan et al., 2004; Emery et al., 2018). Moderate

infestations can cause host anemia and are the most probable cause of anemia in the United States for grazing sheep and goats (Van Wyk and Bath, 2002; Zajac et al., 2016).

The lifecycle of *H. contortus* is direct (Fig. 2) (Roeber et al., 2013). The definitive host (sheep and goats) releases parasite eggs into the environment through host defecation (Roeber et al., 2013). The larvae hatch from the eggs when environmental conditions are optimal for the growth and development of the free-living larvae. The ideal conditions are temperatures over 18 °C and mean precipitation over 5.3 cm (Constable et al., 2017). Table 1 lists twelve of the ecoregions in Texas where small ruminants are produced, along with the mean precipitation and temperature, indicating the Texas climate favors *H. contortus*. More specifically, the Texas climate in spring and summer is optimal for *H. contortus* growth and development (Machen et al., 2017). However, in suboptimal environments, *H. contortus* larvae develop slower (Constable et al., 2017).

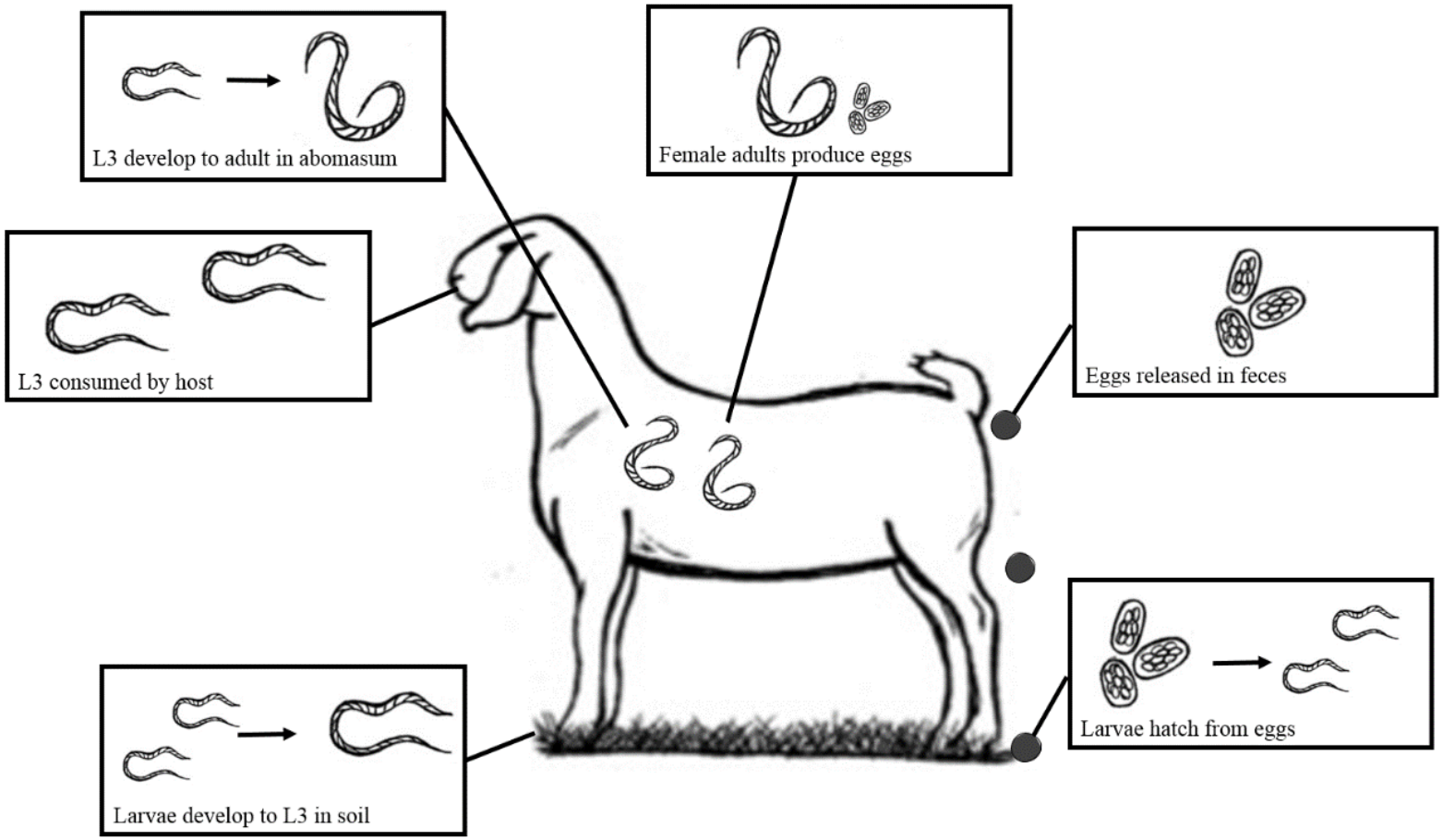

Figure 2. *Haemonchus contortus* Life Cycle. The life cycle starts when the eggs are released in the feces and continues clockwise. L3 is the third stage of larval development.
Source: Machen et al., 2017

Table 1. Mean Precipitation and Temperature for Ecoregions in Texas that Produce Small Ruminants. These locations are favorable for *Haemonchus contortus* infections. These data were pulled directly from the source listed below.

Ecoregion	Mean Temperature, °C	Mean Precipitation, cm
Southwest Plateau and Plains Dry Steppe and Shrub Province		
Pecos Valley	7 to 21	20.0 to 40.0
Texas High Plains	13 to 17	35.0 to 45.0
Rolling Plains	14 to 18	45.0 to 60.0
Edwards Plateau	18 to 20	37.5 to 75.0
Rio Grande Plain	21 to 22	42.0 to 75.0
Southern Gulf Prairies and Marshes	20 to 21	62.0 to 140.0
Chihuahuan Semi-Desert Province		
Basin and Range	13 to 20	20.0 to 32.0
Stockton Plateau	13 to 18	20.0 to 32.0
Prairie Parkland (Subtropical) Province		
Cross Timbers and Prairies	13 to 17	90.0 to 105.0
Blackland Prairies	17 to 21	75.0 to 115.0
Oak Woods and Prairies	17 to 21	70.0 to 110.0
Central Gulf Prairies and Marshes	20 to 21	62.0 to 140.0

Source: McNab, 1996

The larvae go through two stages of development in the soil, from L1 to L2 and from L2 to L3. The transition between the stages involves molting or the shedding of their cuticles, which are external protective layers of the nematode (Roeber et al., 2013). The larvae feed on bacteria until the L3 stage, when their cuticle prevents bacteria consumption but increases the larvae's viability when consumed by grazing animals. The larvae are not infectious until the L3 stage and can travel 90-cm d^{-1} to contaminate even more pasture (Roeber et al., 2013; Constable et al., 2017).

While in the abomasum, the nematodes become sexually mature adults (Machen et al., 2017). As adults, the males and females feed on the host's blood, each consuming 30-µL d^{-1}, and grow to 10-mm and 30-mm long, respectively (Machen et al., 2017; Emery et al., 2018). A single female produces up to 10,000 eggs d^{-1}, making *H. contortus* one of the most fecund nematodes (Levine, 1968; Constable et al., 2017; Machen et al., 2017). The cycle takes a minimum of 21-d (Machen et al., 2017).

Larvae ingested at the beginning of the dry or cold season enter a hypobiotic state, during which all metabolic processes nearly stop (Constable et al., 2017). The larvae resume metabolic processes at the start of the wet or warm season, which often coincides with the time most females are kidding/lambing (Roeber et al., 2013; Constable et al., 2017). This return to an active state causes a dramatic rise in *H. contortus* infection levels.

The first signs of infection occur 18- to 21-d after consuming L3 larvae but can be easily overlooked (Machen et al., 2017). The lifespan of an adult *H. contortus* nematode is several months, which magnifies the initial infection into a potential runaway situation since it only takes 21-d for the nematodes to fully mature (Roeber et al., 2013; Machen et al., 2017). This increased exposure to L3 larvae rapidly increases the parasite load inside a host and further increases anemia and the risk of death from infection (Roeber et al., 2013; Emery et al., 2018).

H. contortus infection does not typically present with observable signs before the host's death (Roeber et al., 2013). The primary sign of infection is anemia due to the L4 larvae and adult *H. contortus* nematodes feeding directly on the blood of their host (Abbott et al., 1986; Sargison, 2012). However, anemia cannot be easily observed, unlike diarrhea and weight loss (Van Wyk and Bath, 2002). Observable signs of severe infections, such as submandibular edema (also called bottle jaw), lethargy, and diarrhea, are frequently overlooked or attributed to other causes (Roeber et al., 2013). Unfortunately, if *H. contortus* infection causes these observable signs before the intervention, the animal will likely die from the infection (Machen et al., 2017).

Controlling *H. contortus* infection is an arduous task for producers around the world. With high fecundity and short generation interval, *H. contortus* proliferates through a herd with very few clinical signs before animals start dying (Kaplan et al., 2004; Roeber et al., 2013). Chemical control using anthelmintics has been the primary means of managing helminth infections in small ruminants.

Anthelmintics and Resistance

Ideal anthelmintics are substances that are toxic to the parasitic nematode but have minimal effects on the host. This selective toxicity is accomplished by targeting processes and structures in the parasite but not in the host (Vercruysse and Claerebout, 2019). Anthelmintics are available in several formulations, such as pour-on, sustained released boluses, feed additives, injectables, drenches, and pastes (McKellar, 1994).

There are four major classes of anthelmintics; benzimidazoles, macrocyclic lactones, amino-acetonitrile derivatives, and imidazothiazoles/tetrahydropyrimidines (Roeber et al., 2013). Benzimidazoles bind to β-tubulin to prevent microtubule formation. This class causes parasitic starvation by preventing the absorption of nutrients from the host (Sargison, 2012; Roeber et al., 2013). Macrocyclic lactones open the glutamate-gated chloride channels leading to paralysis and the eventual death from starvation (Roeber et al., 2013). This class of anthelmintics is also effective against ectoparasites (Waller, 1997). Amino-acetonitrile derivatives attack acetylcholine receptor subunits specific to nematodes (Roeber et al., 2013). Acetylcholine is a neurotransmitter involved in many bodily functions, including muscle movements. Imidazothiazoles and tetrahydropyrimidines cause paralysis in the nematode by acting as

acetylcholine (Roeber et al., 2013). The paralysis results in the expulsion of the nematode from the host (Sargison, 2012; Roeber et al., 2013).

Sustained metaphylactic and prophylactic use of anthelmintics, and subtherapeutic dosing, have contributed to the development of populations of parasites resistant to anthelmintics (Prichard et al., 1980; Kaplan et al., 2004). This underdosing allowed nematodes with resistant genes to reproduce more effectively than their non-resistant counterparts (Sargison, 2012). Multiple anthelmintic resistance is now commonplace worldwide, threatening the economic feasibility of small ruminant production in the affected areas (Waller, 1997; Kaplan et al., 2004). Combination anthelmintics are readily available to producers to help combat anthelmintic resistance (McKellar, 1994).

Although each class of anthelmintics has a different mechanism of action, nematodes have developed resistance to them, primarily by altering the target of the treatments. Benzimidazole resistance is due to a mutation in the β-tubulin gene that prevents the binding of the anthelmintic (Roeber et al., 2013). Macrocyclic lactone resistance is caused by a gene mutation that increases the rate of excretion of the drug from the parasite (Roeber et al., 2013). Amino-acetonitrile derivative resistance is due to the loss of the gene that produces the receptor (Roeber et al., 2013). Resistance to imidazothiazoles and tetrahydropyrimidines is due to structural changes in the receptor that prevent the anthelmintic from binding (Roeber et al., 2013).

The intensive production of sheep and goats has drastically changed how parasitic nematodes interact with their host (Sargison, 2012). Intensive production has increased the stocking rate of these animals, which increases the host's exposure to the infective

stages of the larva (Sargison, 2012). With *H. contortus*, the hosts deposit the same number of eggs into a smaller area, resulting in more frequent reinfection. This increased exposure increases the nematode load inside the host and harms the host (Abbott et al., 1986; Sargison, 2012). Unfortunately, these changes have increased the frequency of anthelmintic use and therefore increased anthelmintic resistance.

Anthelmintic resistance further increases the economic losses of small ruminant producers. Sheep lost 2.8-kg of BW in only 112-d due to resistance alone (Sutherland et al., 2010). Small ruminants with anthelmintic resistant nematode infection sell for 14% less than lambs without resistance due to the reduced weight gain from birth to slaughter (Sutherland et al., 2010).

Mitigating Resistance

Since the development of new pharmaceuticals is unlikely due to the extensive development costs, estimated at $230 million per medication, finding alternatives is becoming increasingly urgent (McKellar, 1994; González-Sánchez et al., 2018). Several strategies have been developed to reduce the negative impacts of parasites on production while mitigating the emergence of anthelmintic resistance. The ideal method for minimizing the emergence of anthelmintic resistance in a herd is to use a combination of strategies (Van Wyk and Bath, 2002).

Fecal Egg Counts

Determining fecal egg counts (FEC) is a popular and effective way to estimate the parasite load in a herd or individual animal (Zajac et al., 2014; Machen et al., 2017). The most common method for FEC is the modified McMaster method, which uses unique slides that allow the evaluator to calculate the number of eggs per gram (EPG) in the host

feces (Zajac et al., 2014). This method involves mixing a fecal sample with specialized solutions that cause heavier debris to sink to the bottom of the container and the lighter eggs to float to the top of the container. This method allows the eggs to be easily isolated from the top of the solution. The number of eggs is then counted on a specialized slide to quantify the infection level (Zajac et al., 2014). Unlike most other nematodes, there is a positive relationship between the EPG in feces and the number of adult *H. contortus* in the abomasum of the small ruminant (Roberts and Swan, 1981). This method allows producers to target anthelmintic treatments to only individuals who need them instead of treating the entire herd. Reducing the number of anthelmintic treatments leaves a more sizable proportion of the nematodes in refugia. Refugia, in this case, is the proportion of nematodes that were not exposed to anthelmintics (Van Wyk, 2001).

Another way FEC can be a valuable tool in mitigating anthelmintic resistance is the FEC reduction test (FECRT). This test assesses the anthelmintic effectiveness by completing another FEC 5- to 10-d after anthelmintic treatment (Waller, 1997; Emery et al., 2016). The timing depends on the anthelmintic used for treatment (Waller, 1997; Emery et al., 2016). The FECRT allows the producer to determine the level of anthelmintic resistance in the nematode population (Emery et al., 2016). If there was a significant decrease in the FEC after anthelmintic treatment, it successfully decreased the nematode load. Conversely, if there is a slight reduction in the FEC after treatment, a high proportion of the nematodes are resistant to the anthelmintic used.

However, the FECRT has several limitations. The major limitation is that it requires at least two pooled samples from at least fifty animals, a sample taken before anthelmintic treatment and the second taken 5- to 10-d after treatment (Levecke et al.,

2011). This requirement is a limitation because producers are unlikely to perform the tests correctly due to the test's susceptibility to processing errors (Waller, 1997). In addition, the aggregated distribution of parasitic nematodes makes it unlikely that over fifty animals will need treatment simultaneously (Barger, 1985; Kaplan et al., 2004).

FAMACHA

Another inexpensive method for assessing *H. contortus* infection level in small ruminant herds is FAffa MAlan CHArt (FAMACHA) scoring (Van Wyk and Bath, 2002). This system uses the color of the ocular conjunctiva to estimate the animal's hematocrit to determine if the animal is anemic (Van Wyk and Bath, 2002). Anemia is clinically diagnosed when the hematocrit, also called packed cell volume (PCV), falls below a certain percentage, depending on the species. As the percentage of red blood cells decreases, the color of the ocular conjunctiva changes from bright red to white (Van Wyk and Bath, 2002). Figure 3 shows a sheep's estimated PCV for each FAMACHA score (Van Wyk and Bath, 2002; Zajac et al., 2016).

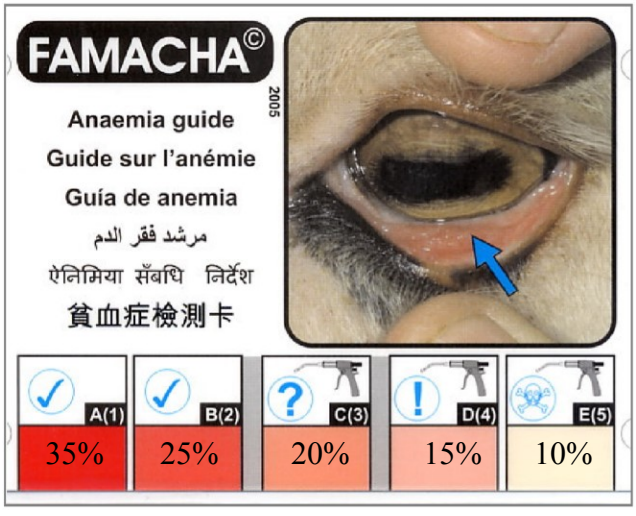

Figure 3. FAffa MAlan CHArt (FAMACHA) and Related Packed Cell Volume (PCV). This chart estimates PCV without a blood sample and can determine *Haemonchus contortus* infection status.
Sources: Van Wyk and Bath, 2002; Zajac et al., 2016

In a study, only the sheep with a light pink to white conjunctiva (FAMACHA scores of 4 or 5, respectively) and bottle jaw were treated at the weekly examination (Van Wyk and Bath, 2002). This treatment protocol resulted in a 90% reduction in treatments (Van Wyk and Bath, 2002). This reduction of anthelmintic use increases the percentage of nematodes in refugia without leaving any animals untreated (Kaplan et al., 2004). Increasing the nematode percentage in refugia reduces anthelmintic resistance by leaving a proportion of the nematodes unexposed to the anthelmintic (Van Wyk, 2001).

Since FAMACHA was designed in Africa using sheep, its utility was evaluated on sheep and goats in the southeastern United States. Kaplan et al. (2004) assessed the FAMACHA score's ability to identify anemic animals in 847 sheep and 537 goats. Their research indicated a significant correlation between PCV, FEC, and FAMACHA scores for sheep and goats. Therefore, they confirmed that FAMACHA scores could be used to identify animals that need anthelmintic treatment due to the anemia caused by *H. contortus*.

Furthermore, Kaplan et al. (2004) determined that 89% of treatments were correct for sheep and 71% for goats when using a FAMACHA score of 4 or 5 as a requirement for treatment. More importantly, only 0.5% of substantially infected sheep and 0.6% of substantially infected goats were left untreated when a score of 4 or 5 determined anthelmintic treatment, i.e., when anemia was defined as a PCV less than 15%. The authors recommend treating all animals with a FAMACHA score of 4 or 5. Additionally, they recommend treating animals with a FAMACHA score of 3 only when there are other signs of infection, such as fatigue, weight loss, inappetence, and bottle jaw (Kaplan et al., 2004; Zajac et al., 2016)

The FAMACHA system has six limitations. The most prevalent economic limitation is that it does not identify infections from helminths other than *H. contortus*, such as *Trichostrongylus axei* and *Fasciola hepatica*, which also cause reduced weight gain and death (Van Wyk and Bath, 2002; Kaplan et al., 2004). Another limitation of FAMACHA is that it is subjective and has only five categories that result in incorrect categorization up to 44% percent of the time (Van Wyk and Bath, 2002). However, 71% of the incorrect estimates were only one category off, and less than 3% of animals that required treatment did not receive treatment (Van Wyk and Bath, 2002). Another limitation is that it measures anemia by factors other than *H. contortus* infection, such as nutritional deficiencies and ingestion of toxins (Van Wyk and Bath, 2002; Kaplan et al., 2004).

A fourth limitation is that during peak *H. contortus* infection times, FAMACHA scores are recommended weekly, as the PCV of a sheep can decrease by 7% in only 1-wk, potentially leading to death depending on the severity of anemia (Van Wyk and Bath, 2002). A fifth limitation is that the FAMACHA score was designed for sheep and is not optimal for goats. Goats have a smaller range in ocular conjunctiva color, which makes the FAMACHA system more challenging to use in goats (Van Wyk and Bath, 2002; Kaplan et al., 2004). The sixth limitation is that it is only effective on adult sheep and goats. Infection of the young can result in much higher blood loss than in adults. Since the young have a weaker immune system and smaller blood volume, FAMACHA is not an adequate measure of *H. contortus* loads (Kaplan et al., 2004). Kaplan et al. (2004) also recommended a more liberal treatment decision with periparturient and lactating animals since they also have decreased immunity.

Alternative Anthelmintics

There is growing interest in evaluating alternative treatments for parasite infections in small ruminant operations. One example is using fungi as an alternative to anthelmintics; *Arthrobotrys oligospora* has been investigated for its ability to feed on gastrointestinal nematodes in the feces of sheep and goats (Cai et al., 2017). This fungus is a natural predator of nematodes. Another alternative is developing a vaccine against parasites, such as the recombinant DNA vaccine against *H. contortus* in sheep (González-Sánchez et al., 2018).

Yet another area of investigation is using bioactive plants with anthelmintic activity (Palacios-Landín et al., 2015). A significant limitation to these studies is that the bioactive plants were administered as a treatment, not as an *ad libitum* feedstuff. The former has the possibility of increasing resistance to these new bioactive plant-based anthelmintics at the same rate as current pharmaceuticals. An alternative to slow the incidence of resistance is the host's *ad libitum* consumption of these bioactive plants. This consumption is called self-medicating (Hart, 2005).

Self-Medication

One of the first mentions of self-medicating for parasite infections in small ruminants was by Hutchings et al. (2003). Three behavior adaptations to parasitic infections were discussed: avoiding contaminated areas, ingesting nutrients consumed by the parasite, and ingesting bioactive plants. How an individual host balances these three adaptations directly affects their ability to combat infections (Hutchings et al., 2003).

Amit et al. (2013) conducted a 3-phase experiment to evaluate the capacity of goats to self-medicate with bioactive plants. The first phase involved providing each

treatment group with a different forage (*Pistacia lentiscus*, *Phillyrea latifolia*, and clover hay) after infecting the subjects with nematodes obtained from an infected animal in the same region. The second phase involved only providing clover hay. The third phase involved providing all treatment groups access to all three forages for 2-h d^{-1}. Researchers determined that goats with access to forage other than just clover hay were more likely to consume the anthelmintically active *P. lentiscus*. However, researchers also determined no relationship between infection and intake of *P. lentiscus* in the Damascus goats, but there was a relationship in the Mamber breed (Amit et al., 2013).

Factors Affecting FEC

Yet another alternative to control nematode infections in small ruminants is to manipulate the environment so that they will not be as susceptible to nematodes. Some characteristics, or factors, of small ruminants can affect their susceptibility to gastrointestinal nematode infections. A few examples are breed, pregnancy status, sex, age, and the month of the year.

There are numerous accounts of breed affecting FEC. Table 2 lists a few breeds of sheep and goats with varying relative susceptibility to gastrointestinal nematode infections. Overall, the Gulf Coast Native and St. Croix sheep breeds and the Spanish and Kiko goat breeds are usually less susceptible to infection (Emery et al., 2018; Wang et al., 2017). Their superiority is likely due to their increased immune response, but the exact mechanisms are yet to be elucidated (Gamble and Zajac, 1992; Bahirathan et al., 1996; Shakya et al., 2009). The heritability estimates for susceptibility to gastrointestinal nematodes range from 0.01 to 0.65, indicating that susceptibility is a polygenic trait (Zvinorova et al., 2016). However, there does seem to be a trend with the less susceptible

breeds coming from extensively managed practices (Zvinorova et al., 2016). Most importantly, there is considerable variation within the same breeds of small ruminants (Gamble and Zajac, 1992; Shakya et al., 2009).

Table 2. Relative Susceptibility of Various Breeds of Sheep and Goats.

Species	Breed	Susceptibility	Source(s)
Sheep	Barbados Blackbelly	Low	Constable et al., 2017; Emery et al., 2018
	Dorset	High	Gamble and Zajac, 1992
	Gulf Coast Native	Low	Bahirathan et al., 1996; Shakya et al., 2009; Constable et al., 2017; Emery et al., 2018
	Hampshire Down	High	Constable et al., 2017
	Katahdin	Low	Machen et al., 2017
	Red Maasai	Low	Constable et al., 2017; Emery et al., 2018
	Royal White	Low	Machen et al., 2017
	Scottish Blackface	Low	Constable et al., 2017
	St. Croix	Low	Gamble and Zajac, 1992; Constable et al., 2017; Machen et al., 2017; Emery et al., 2018
	Suffolk	High	Bahirathan et al., 1996; Shakya et al., 2009
Goat	Boer	High	Nguluma et al., 2013; Wang et al., 2017
	Galla	High	Baker et al., 1998
	Kiko	Low	Nguluma et al., 2013; Wang et al., 2017
	Myotonic	Low	Wang et al., 2017
	Small East African	Low	Baker et al., 1998
	Spanish	Low	Nguluma et al., 2013; Wang et al., 2017

Thomas and Ali (1983) devised one of the first accounts displaying FEC variations by pregnancy status. Further research also indicated that pregnant and lactating females are more susceptible to infections (Baker et al., 1998; Kaplan et al., 2004; Vanimisetti et al., 2004; Wang et al., 2017). However, the increased susceptibility varies among breeds (Baker et al., 1998; Wang et al., 2017). Notter et al. (2017) determined that if an ewe is nursing twins or triplets, they had a higher FEC.

Sex can also impact the FEC. Vanimisetti et al. (2004) showed that post-pubertal female lambs are less susceptible to parasitic infections than age-matched males. Additionally, there was no difference between male and female lambs before puberty (Vanimisetti et al., 2004).

Age can also affect FEC, as younger goats do not have the rigorous immune response of older goats (Kaplan et al., 2004; Roeber et al., 2013). Moreover, Constable et al. (2017) indicated that most livestock losses are from young animals due to their lower blood volume. The lower volume intensifies the proportionate blood loss of a given intensity of *H. contortus* infection. Gamble and Zajac (1992) also indicated that lambs are more susceptible to parasitic nematodes for the first year of life, and their susceptibility decreases after 1-yr of age. This trend was confirmed with continual experimental reinfections (Vanimisetti et al., 2004). Notter et al. (2017) found that younger ewes had higher FEC than older ewes during periparturient periods. They also found that this increase in FEC was also seen in their lambs (Notter et al., 2017). There was also an increase in FEC after 2-yr of age as they approached 7-yr of age in dry female goats, but not in female production goats (Wang et al., 2017).

Each gastrointestinal nematode species has its season of proliferation based on the environmental conditions conducive to larval development and its subsequent infection of hosts. The work of Van Wyk and Bath (2002) and Roeber et al. (2013), and Emery et al. (2016) supports the seasonality of parasitic nematode infections. In addition, Mederos et al. (2010) documented the seasonal variation of five distinct species of nematodes over a 15-mo period in Canada. Similarly, Sutherland et al. (2010) showed seasonal changes in the percentages of three species of nematodes over a 4-mo period in New Zealand.

Furthermore, there were significantly different *H. contortus* egg production levels depending on the month in Australia (Roberts and Swan, 1981). They suspected this trend was due to larvae entering and leaving hypobiosis (Roberts and Swan, 1981). This trend is also seen in the United States (Vanimisetti et al., 2004; Zajac et al., 2016).

Specifically, in Texas, the *H. contortus* infection season is between spring greenup and the first frost (Machen et al., 2017).

Goals and Objectives

This study was based on the hypothesis that (all things else constant) that breed and age, among other factors, will affect a goat's gastrointestinal infection level. This study's goal was to determine the degree to which breed, age, and other factors are correlated with FEC to help producers make management decisions. Specifically, the objectives of this study were to:

1. determine weekly FEC for the herd of goats at the Freeman Center for over 1-yr, and
2. determine the relationships between assessed factors and the FEC measures.

Related assumptions are that the dispersal of nematodes among hosts will be aggregated and that the resulting FEC frequency table can be adequately described by the negative binomial (NB) expectation. Determining which factors affect a goat's FEC can give producers another tool to help combat the economic and physiological toll of parasitic infections in a world with increasing anthelmintic resistance.

III. MATERIALS AND METHODS

Study Site

All animal work was approved by Texas State University's Institutional Animal Care and Use Committee, Protocol #7228. This study used the goat herd at the Freeman Center (29.938053, -98.008424) in Hays County, San Marcos, Texas. The animals used were the three Boer goats, nine Spanish goats, and twenty-seven Spanish-Boer crossbred goats.

The goats had access to 2.93-ha of native forage and were supplemented with *ad libitum* hay and trace mineral licks. The goats also had *ad libitum* access to fresh water. The goats were monitored daily for abnormal feces and unusual behavior, such as separation from the herd, panting, and lethargy throughout the experiment.

Weekly Samples

Weekly samples were collected from each goat to assess animal health. The weekly sample collection for this study consisted of fecal samples used to determine FEC. In addition to these samples, PCV, BW, FAMACHA, overall appearance, and behavioral abnormalities were noted to assess animal health throughout the study. If a goat required anthelmintic treatment or had abnormal samples, the goat was isolated, and a veterinarian was consulted when necessary.

Trained workers collected fecal samples every week by placing one to two fingers of a gloved and lubed hand into the goat's rectum, removing several fecal pellets (Zajac et al., 2014). Once the fecal pellets were in the gloved hand of the sample collector, the glove was turned inside out, tied, labeled with the goat's tag number, placed in a cooler (at 0 °C), and subjected to FEC analysis within 24-h of collection (Zajac et al., 2014).

Fecal egg counts were determined using a modified McMaster procedure for each weekly fecal sample (Zajac et al., 2014). Briefly, 2-g of crushed feces was removed from each sample and mixed with 28-mL of magnesium sulfate fecal float (specific gravity: 1.25 to 1.27-g mL^{-1}). After 5-min of flotation, the samples were strained with 1.68-mm mesh and left undisturbed for an additional 5-min before being loaded into a McMaster slide (FEC Source, Grand Ronde, OR). Three separate chambers of a McMaster slide were counted as triplicate estimates, and the mean was calculated to determine the mean FEC for each sample. The mean FEC was then multiplied by fifty to estimate the Eggs per Gram (EPG) for each sample, which is the standard reporting unit for FEC (Zajac et al., 2014). Therefore, the sensitivity of the McMaster slide was 50 EPG (Zajac et al., 2014).

Goats were treated with fenbendazole or moxidectin when their EPG estimate was above the critical limits set by Machen et al. (2017). The goat was treated if a non-pregnant, non-lactating female goat had an EPG higher than 2,000 EPG. The same treatment threshold was used for male goats over 1-yr of age. However, if a female was pregnant or lactating, she was treated if her EPG was more than 1,000. Additionally, all kids under 1-yr of age were treated at > 1,000 EPG (Machen et al., 2017).

Statistical Analysis

Regression analysis was used to determine the factors that could predict a goat's FEC because it allows for the simultaneous analysis of multiple factors in one test. It also determines the effect of each factor independent of the others. A general linear model regression analysis was used to determine each factor's potential impact on an

individual goat's FEC using the weekly FEC data and R version 4.1.1 (R Core Team, 2021).

The regression models assessed were linear, Poisson, negative binomial (NB), zero-inflated Poisson (ZIP), and zero-inflated negative binomial (ZINB). The Poisson regression was evaluated because FEC data are all positive whole numbers, making them discrete or count data. Discrete data often follow the Poisson distribution unless the variance exceeds the mean (Barger, 1985). Determining aggregation can be done by calculating k, the inverse of the aggregation level (where $k = \frac{\bar{X}^2}{(s^2 - \bar{X})}$, $s =$ standard deviation of counts, and $\bar{X} =$ mean of counts) (Galvani, 2003). If the value of k is less than one, it signifies aggregation (Galvani, 2003). Since FEC data tends to be aggregated, it was expected to follow the NB, which was also assessed. Furthermore, since a substantial portion of the FEC data were zero, the ZIP and ZINB regression models were also assessed (Galvani, 2003).

The mass package in R was used to run the NB model (Venables and Ripley, 2002). The pscl package in R was used to run the two zero-inflated models (ZIP and ZINB) (Zeileis et al., 2008). The model with the lowest Akaike information criterion (AIC) was used to interpret the data. It measures how well the data fit the regression model (Akaike, 1973).

Data validation excluded data from the regression models for three reasons to ensure the assessed models accurately represent the FEC data. One reason was if an anthelmintic was given within the last 3-wk to account for the medication withdrawal periods. Another reason for excluding data were if it had been collected during a feeding trial using potential bioactive plants that can affect FEC. Both reasons can decrease the

egg output due to nematode death, and this decrease can distort the FEC as a measure of parasite intensity. The third reason data were excluded was if less than 2-g of feces were used to get the FEC since the decreased volume could increase debris interference in the sample and bias the FEC.

The factors used in this study were breed, sex, age, and collection month. There are numerous accounts of breed affecting FEC (Gamble and Zajac, 1992; Bahirathan et al., 1996; Nguluma et al., 2013; Constable et al., 2017; Machen et al., 2017; Wang et al., 2017; Emery et al., 2018). Sex was added to the regression to determine if there was a difference independent of pregnancy status (Thomas and Ali, 1983; Baker et al., 1998; Kaplan et al., 2004; Vanimisetti et al., 2004). Several studies indicate that age affects FEC (Gamble and Zajac, 1992; Kaplan et al., 2004; Vanimisetti et al., 2004; Roeber et al., 2013; Constable et al., 2017). The collection month was added since different species of gastrointestinal nematodes have distinct seasons of proliferation (Roberts and Swan, 1981; Van Wyk and Bath, 2002; Vanimisetti et al., 2004; Mederos et al., 2010; Sutherland et al., 2010; Roeber et al., 2013; Emery et al., 2016; Zajac et al., 2016; Machen et al., 2017ar).

Although pregnancy status can affect FEC, it was omitted from this study due to its interaction with sex (Thomas and Ali, 1983; Baker et al., 1998; Kaplan et al., 2004; Vanimisetti et al., 2004). The correlation between sex and pregnancy status in this study was due to the management decision to breed all sexually mature females (all Spanish breeds) to a single intact male (Boer breed). Additionally, the study's short duration did not allow the offspring to mature sexually and breed. This correlation could be minimized by analyzing only females' FEC data or increasing the study duration.

The FEC measures were treated as a continuous numeric variable. The breed was treated as a dummy variable, with each breed having its own dummy variable. The goat's sex was treated as a dummy variable, with one being female and zero being male. Age was treated as a continuous numeric variable. The twelve collection months were treated as dummy variables, with each month having its own dummy variable. The factors were considered significant if the *P*-value was less than 0.05.

IV. RESULTS

There were 988 FEC samples that met the inclusion criteria for this study between September 2018 and January 2020 on thirty-nine goats at the Freeman Center. The FEC data were expected to follow the negative binomial distribution instead of the normal distribution. The AIC values, Vuong's non-nested test results, log-likelihood ratio test results, and log-likelihood values were used to validate that the FEC data follows the negative binomial distribution.

The FEC values ranged from 0 EPG to 2700 EPG. The FEC varied within and between each goat. Figure 4 shows the distribution of FEC data for each goat in EPG of feces. The FEC values for 40, 41, and 42 represent Goat B, W, and Wi, respectively.

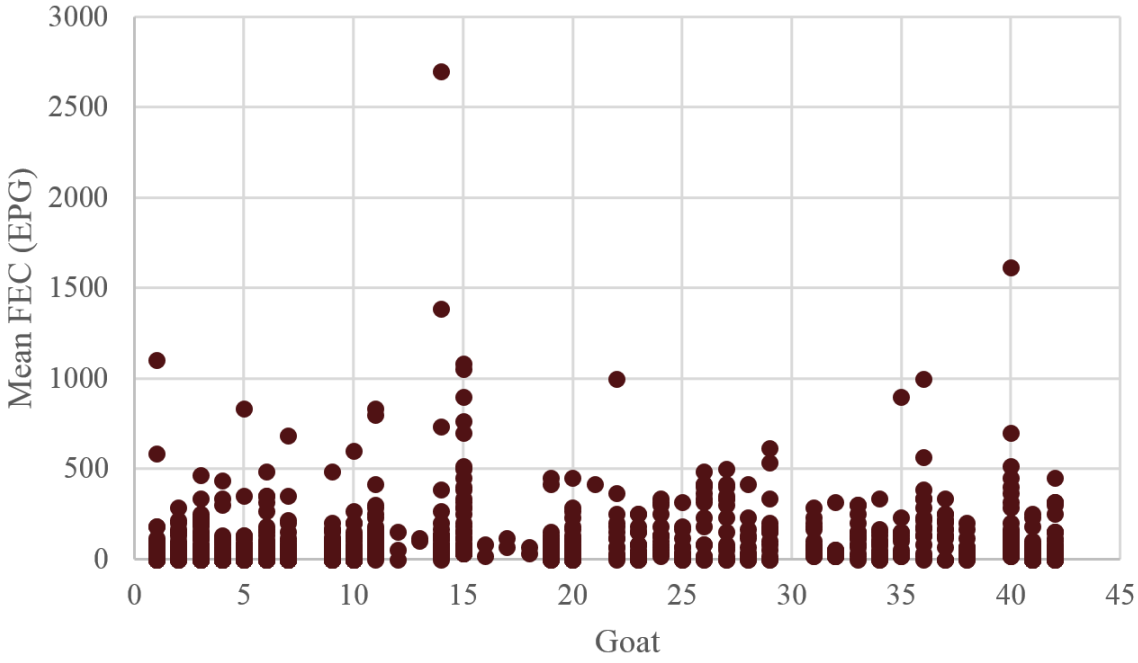

Figure 4. Distribution of Mean Fecal Egg Counts (FEC) for each Goat in Eggs per Gram (EPG) of Feces. The FEC values for 40, 41, and 42 are Goat B, W, and Wi, respectively.

Table 3 shows the mean FEC by included factors, the total number of samples for each value of the included factors, and the percentage of all FEC collected. The overall

mean FEC was 103.0 EPG. The Spanish breed had a mean FEC of 62.9 EPG compared to 96.9 for the Boer breed and 142.5 for the Spanish-Boer crossbred goats. The mean FEC for females was 98.3 EPG and 118.7 EPG for males. Goats under 6-mo of age had a mean of 128.6 EPG, which tended to decrease until age 7-yr, when the mean increased to 241.9 EPG. This peak is due to only having one goat (Goat B) reach that age during the study. November was the month with the lowest mean FEC with a value of 53.2 EPG, and April had the highest mean of 176.3 EPG.

Table 3. Mean Fecal Egg Counts (FEC) in Eggs per Gram (EPG) of Feces for Factors Considered for this Study.

Factor	Mean FEC (EPG)	Number of Samples	Percentage of FEC Values
Breed			
Spanish	62.9	417	42.2
Boer	96.9	127	12.9
Cross	142.5	444	44.9
Sex			
Female	98.3	758	76.7
Male	118.7	230	23.3
Age			
< 6-mo	128.6	138	14.0
6-mo to 1-yr	160.5	233	23.6
1-yr	111.3	73	7.4
2-yr	86.3	43	4.4
3-yr	16.5	4	0.4
4-yr	65.6	392	39.7
5-yr	20.6	25	2.5
6-yr	81.1	7	0.7
7-yr	241.9	25	2.5
8-yr+	39.8	48	4.9
Collection month			
January	65.1	86	8.7
February	91.7	56	5.7
March	125.8	46	4.7
April	176.3	71	7.2
May	155.1	55	5.6
June	100.7	117	11.8
July	143.3	126	12.8
August	121.1	125	12.7
September	71.0	84	8.5
October	61.0	94	9.5
November	53.2	67	6.8
December	65.5	61	6.2
All data	103.0	988	100

The distribution of the FEC data is represented in Fig. 5 and 6. Figure 5 shows the distribution of all FEC, and Figure 6 is a boxplot of the data. If the FEC data were normally distributed, the density plot in Fig. 5 would be a bell-shaped curve, as shown in grey in the figure (Urdan, 2017). Additionally, if it were normally distributed, the boxplot would resemble a box with very few values falling above or below the whiskers, as shown in grey in the figure. If the observations are count data from a defined sampling unit, it could either follow the Poisson distribution or the NB distribution (Ireland, 2010; Urdan, 2017).

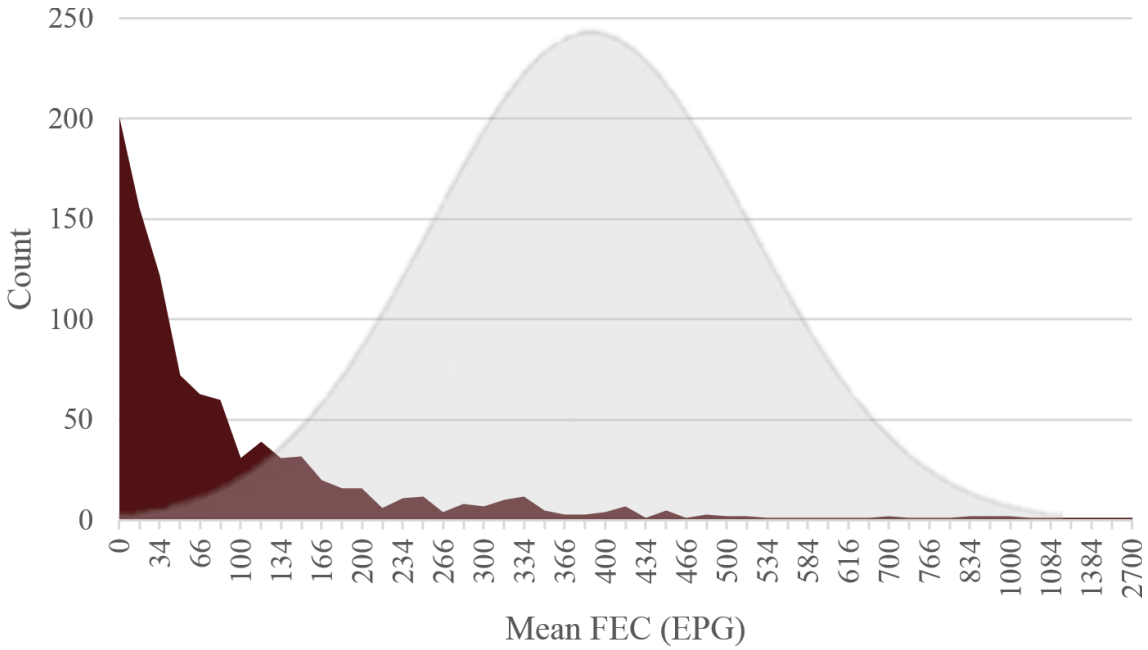

Figure 5. Frequency Distribution Table of Mean Fecal Egg Counts (FEC) in Eggs per Gram (EPG) of Feces. If the mean FEC were normally distributed, the data would be similar to the grey bell-shaped curve. The dissimilarities indicate that it does not follow the normal distribution.
Sources: Urdan, 2017; McLeod, 2019a

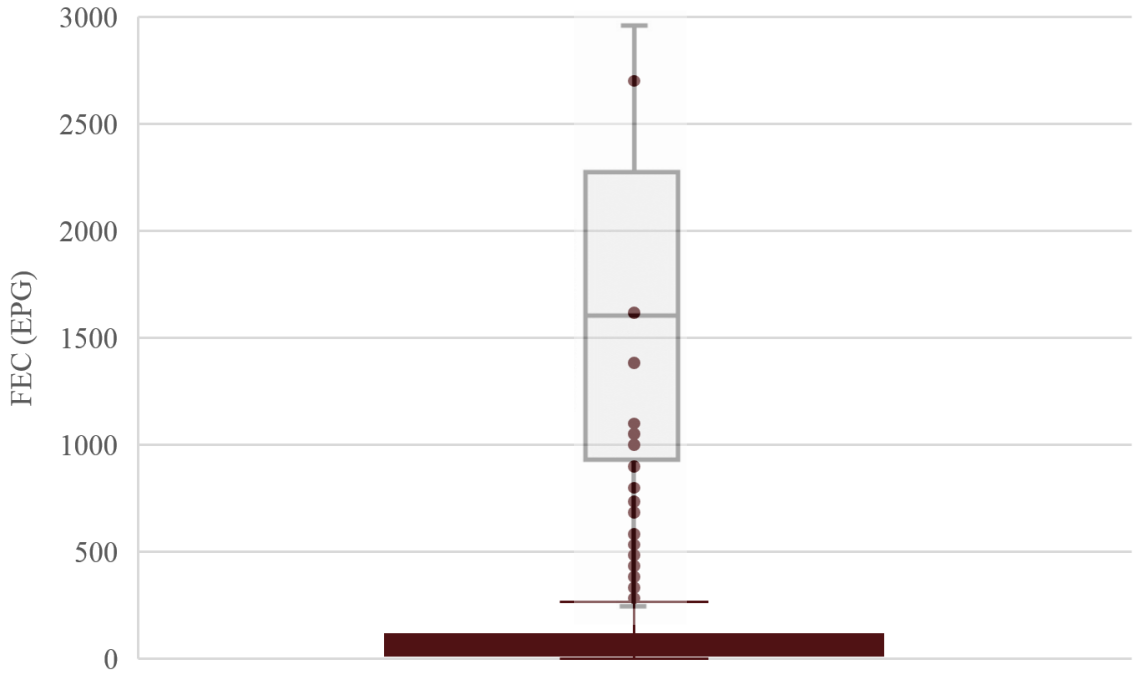

Figure 6. Boxplot of Fecal Egg Counts (FEC) in Eggs per Gram (EPG) of Feces. If the mean FEC were normally distributed, the data would be similar to the grey box plot. The dissimilarities indicate that it does not follow the normal distribution. *Sources: Barger, 1985; Ireland, 2010; Urdan, 2017; McLeod, 2019b*

The FEC data were aggregated, as indicated by the value of *k* in this study (1.03 x 10^{-5}), which suggests the data are extremely aggregated. Additionally, the variance, 32035.6 EPG^2, was much greater than the mean, 103.0 EPG, which indicates the data violates the assumption of the Poisson distribution that the mean is equal to the variance (Barger, 1985). When aggregation occurs, the frequencies follow the NB distribution (Barger, 1985). There were 551 samples that were at or below the detectable level of 50 EPG (Fig. 7). Moreover, 201 samples had a value of zero which means the goat's FEC for all three triplicate estimates (Fig. 7), which indicates the data follows a zero-inflated distribution, and that the zero-frequency class is contaminated with samples that are not part of the infection process.

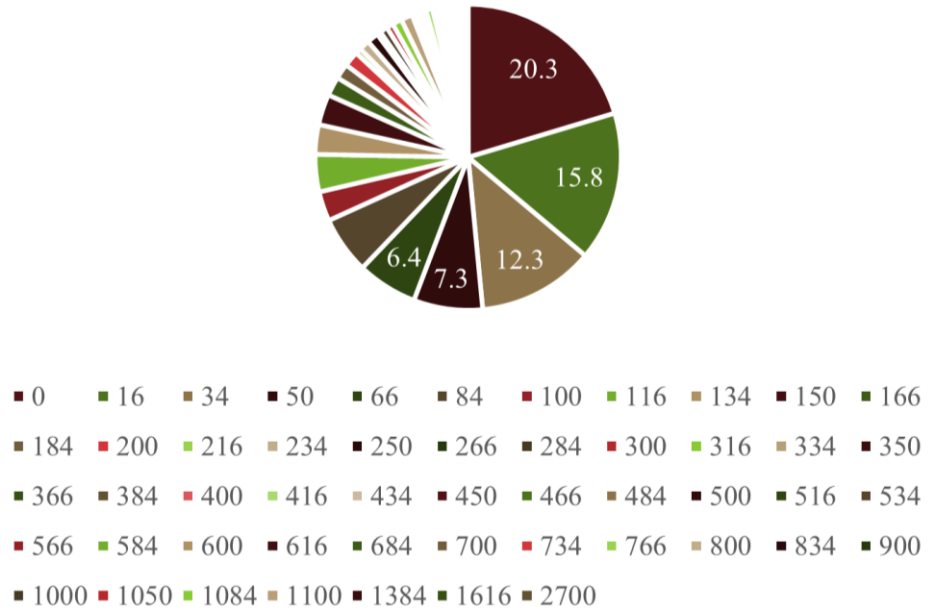

Figure 7. Distribution of Fecal Egg Counts (FEC) in Eggs per Gram (EPG) of Feces.

The fit of the evaluated models is represented in Tables 3 and 4. The two Poisson models (Poisson and ZIP) had the largest AIC, which indicates a poor fit. Additionally, they were a poor fit because the data are highly aggregated, meaning the variance far exceeds the mean (Yang et al., 2017). The linear model was a better fit than the two Poisson models but was still poor because the data were skewed left and did not approximate the normal distribution without transformation (Yang et al., 2017). The NB model had a lower AIC value than the linear model. This result is consistent with previous research (Barger, 1985; Jones et al., 1991). However, its poor fit is attributed to the excess zeros. Finally, the ZINB model had the lowest AIC with a value of 10070.5, indicating the best fit of the models assessed.

In the case of parasitic infections, an FEC value of zero can come from two sources: 1. no infection, or 2. an infection below the detectable limits. The zero-inflated models account for both causes of zero FEC values because the zero-inflated models

have two parts. The first part is a Poisson or NB model that assesses the non-zero variation of FEC, excluding all zero values. The second part determines the likelihood of a goat getting a true zero FEC value, meaning it has no infection.

Additionally, Vuong's non-nested tests (Table 4) also indicated that the ZINB model fit best ($P < 2.2 \times 10^{-16}$). Furthermore, the log-likelihood ratio tests showed that the ZINB regression model fits significantly better than the other models ($P < 0.001$). Moreover, the ZINB regression had the highest log-likelihood values, indicating the best fit. The results subsequently discussed in this paper are based on the ZINB model.

Table 4. Vuong Non-nested Tests Results

Model Comparison	Vuong Test Statistic	*P*	Preferable Model
Poisson vs. NB	-21.0	$< 2.2 \times 10^{-16}$	NB
NB vs. ZIP	17.3	$< 2.2 \times 10^{-16}$	NB
NB vs. ZINB	-10.7	$< 2.2 \times 10^{-16}$	ZINB

The regression coefficients for each of the five models evaluated are in Table 5. The standard errors (in parentheses) varied substantially between tests. The Poisson models (Poisson and ZIP) tended to have smaller standard errors. This trend resulted in all factors being inaccurately significant due to excess Type 1 errors (Yang et al., 2017).

Table 5. Effects of Factors on Fecal egg counts (FEC) in Eggs per Gram (EPG) of Feces. The standard errors are shown in parentheses.

Factor	Linear		Poisson		Negative Binomial		Zero-inflated Poisson		Zero-inflated Negative Binomial	
Intercept	31.5	(36.4)	37.4***	(1.0)	25.6***	(1.4)	53.1***	(1.0)	45.8***	(1.3)
Breed										
Spanish										
Boer	17.6	(27.9)	1.3***	(1.0)	1.4	(1.3)	1.0*	(1.0)	1.0	(1.2)
Cross	79.2**	(25.1)	2.3***	(1.0)	3.5***	(1.3)	2.0***	(1.0)	2.3***	(1.2)
Sex										
Female	-15.5	(19.7)	0.8***	(1.0)	0.8	(1.2)	0.8***	(1.0)	0.8	(1.1)
Male										
Age	0.0	(0.1)	1.0***	(1.0)	1.0	(1.0)	1.0***	(1.0)	1.0	(1.0)
Collection Month										
January	11.1	(28.2)	1.2***	(1.0)	2.1**	(1.3)	1.3***	(1.0)	1.6*	(1.2)
February	47.2	(31.4)	1.9***	(1.0)	3.1***	(1.3)	1.6***	(1.0)	2.0**	(1.2)
March	79.5*	(33.2)	2.6***	(1.0)	3.5***	(1.4)	2.0***	(1.0)	2.3***	(1.2)
April	128.2***	(29.6)	3.5***	(1.0)	4.8***	(1.3)	2.7***	(1.0)	3.1***	(1.2)
May	107.8***	(31.6)	3.1***	(1.0)	3.4***	(1.3)	2.4***	(1.0)	2.4***	(1.2)
June	25.7	(26.7)	1.5***	(1.0)	1.4	(1.3)	1.5***	(1.0)	1.5*	(1.2)
July	70.3**	(26.3)	2.2***	(1.0)	2.2**	(1.3)	2.1***	(1.0)	2.1***	(1.2)
August	47.7	(26.4)	1.9***	(1.0)	1.7*	(1.3)	1.6***	(1.0)	1.6**	(1.2)
September	12.4	(28.3)	1.3***	(1.0)	1.3	(1.3)	1.2***	(1.0)	1.3	(1.2)
October	10.5	(27.6)	1.2***	(1.0)	1.2	(1.3)	1.2***	(1.0)	1.2	(1.2)
November										
December	20.9	(30.7)	1.4***	(1.0)	1.5	(1.3)	1.3***	(1.0)	1.4	(1.2)
Observations	988		988		988		988		988	
Log-likelihood					-10,331.9		-58,070.0		-4,979.0	
AIC	12,998.0		147,902.0		10,363.9		116,207.9		10,070.5	

Note: The dependent variable is fecal egg count (FEC) in Eggs per Gram (EPG) of Feces. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$

The FEC for the Spanish-Boer crossbred goat (142.5 EPG) was statistically higher than the other two breeds ($P < 0.001$). Being a Spanish-Boer crossbred goat increased its FEC by 2.3 EPG. The sample sizes between breeds varied substantially. There were 417 samples from the Spanish breed and 127 from the Boer breed. The Spanish-Boer crossbred goats had 444 samples.

The goat's sex did not significantly affect its FEC in this study. Additionally, the goat's age did not significantly influence its FEC, although previous research has indicated that young goats tend to have higher FEC than mature goats.

The FEC for the collection month was significant from January through August ($P < 0.05$). The sample sizes varied between collection months. March had the lowest number of samples, with 46 samples. July had the most samples, with 126 samples.

V. DISCUSSION

This study analyzed weekly fecal samples from thirty-nine goats for 16-mo to determine each goat's FEC over time. The FEC data were used to determine which factors affected the FEC of the study goats. The proposed work hypothesized that several factors, including breed and age, will affect a goat's gastrointestinal infection level. Regression analysis was used to determine the relationship of each factor to the FEC, and the ZINB was the best fit model.

The data that were used in this study varied substantially. The variation in FEC between each goat is due to its individual susceptibility to gastrointestinal nematode infection. It results from the aggregated distribution of parasites among a host population (Barger, 1985; Jones et al., 1991; Kaplan et al., 2004). Several variables can affect a goat's susceptibility. They include the quality and quantity of feed and forage, the host's health status and immune response, the infecting nematode species, the intensity of the infection, and the host's stocking rate (Greer, 2008; Sargison, 2012; Amit et al., 2013; Roeber et al., 2013).

Additionally, each goat's FEC varied each week due to variation in its susceptibility over time (Gamble and Zajac, 1992; Shakya et al., 2009). However, a few goats stand out as having the highest FEC at one time or another. For example, Goat 14 had an FEC of 2700 EPG, and Goat B had an FEC of 1616 EPG.

Breed

In this study, the Spanish-Boer crossbred goats had higher FEC than the other two breeds. This result is inconsistent with Nguluma et al. (2013), where there was no significant difference in FEC at weaning between Boer, Spanish, and Spanish-Boer

crossbred goats (Nguluma et al., 2013). In addition, Nguluma et al. (2013) and Wang et al. (2017) found that Spanish breed goats are less susceptible to infection but poorer performers than the Boer breed, which was not observed in this study. This discrepancy could be due to the age differences in the study goats. The Spanish-Boer crossbred goats were substantially younger than the other two breeds and had not fully developed their immunity to *H. contortus* as they were only 4-mo old at the start of this study. Furthermore, Vanimisetti et al. (2004) and Notter et al. (2017) indicated that immunity to parasitic infections reaches its peak at 1-yr of age.

Month

In this study, the months January through August were significant. This significance was expected because *H. contortus* starts its proliferation season when temperatures are optimal for the development of larvae and continues until the first frost (Constable et al., 2017; Machen et al., 2017). When environmental conditions are optimal, large numbers of infective larvae contaminate the soil and quickly cause small ruminants to present with signs of clinical haemonchosis (Roeber et al., 2013; Constable et al., 2017; Machen et al., 2017). Even in sub-optimal conditions, the larvae can still develop (Constable et al., 2017).

The start of *H. contortus* larval development usually coincides with kidding or lambing (Roberts and Swan, 1981). In this study, the Spanish female goats began kidding in mid-January 2019, which may attribute to the start of nematode development in January.

This study used over one year of weekly FEC measures from a herd of goats to determine the relationships between assessed factors and their FEC measures.

Specifically, this study showed that the breed and month of the year significantly impact an individual goat's FEC. Furthermore, this study compared five regression models and found that the ZINB model was the best fit. This information can help reduce the physiological and economic toll of parasitic nematode infections.

Suggested Management Practices

Several management practices could help ease the nematode burden on individuals and a herd. Even though it is out of the scope of this study, a few management practices are listed for consideration in future studies. Some management practices include targeted treatments, culling decisions, and introducing less susceptible breeds to a herd.

Targeted treatment reduces drug costs but increases overall production costs (Barger, 1985). Additionally, treating only 21% of a herd reduces the mean herd nematode load by 50%. It also increases the proportion of nematodes in refugia and decreases selection pressure for anthelmintic resistance (Barger, 1985). This reduced selection pressure can mitigate anthelmintic resistance in a herd which substantially reduces the profitability of productions (Sutherland et al., 2010). Targeted treatments can reduce treatments by up to 90% (Van Wyk and Bath, 2002). They reduce the output of eggs from the host and, subsequently, L3s in the soil (Cai et al., 2017). The decreased quantity of L3s in the soil helps hosts develop immunity and resilience since the animals are exposed to manageable levels of infective larvae (Van Wyk, 2001). Additionally, treating while nematodes are still in hypobiosis can substantially reduce the infection level of a goat and therefore reduce clinical signs of haemonchosis (Constable et al., 2017).

To help decrease susceptibility to gastrointestinal nematode infection in a herd and consequently reduce the mean FEC for a herd, a producer could choose to cull the animals with the highest FEC each season. Alternatively, Hoste and Torres-Acosta (2011) recommend culling any animals that require multiple anthelmintic treatments. Most of the goats in this study (30 total) never required anthelmintic treatment. Hoste and Torres-Acosta (2011) also recommend culling the lowest-producing animals. However, Greer (2008) cautions that selecting productivity traits alone can lead to a herd with relatively high FEC output, as seen in the Romney breed of sheep.

To improve the herd's FEC, a producer can introduce breeds known to be less susceptible to infection. However, these goats must have a proven low FEC and come from a source that does not already have anthelmintic resistance. Otherwise, the introduction of anthelmintic resistance genes may have damaging profitability effects. Using these techniques, a producer can reduce parasitic nematode infections' physiological and economic toll.

Caveats

The variability in sample size for each breed is due to the small number of Boer goats (three goats) used in this study and the management decision to breed all the Spanish goats (nine goats) to the one intact male (Goat B), who was a Boer goat. This decision also resulted in all the Spanish-Boer crossbred goats being substantially younger than the Boer goats or Spanish goats. This age disparity could result in an arbitrarily higher FEC for Spanish-Boer crossbred goats because younger goats have a less developed immune system than older goats (Kaplan et al., 2004; Roeber et al., 2013; Machen et al., 2017). This disparity may also contribute to this study's nonsignificant

relationship between age and a goat's FEC since each breed had minimal age overlap during the study. Additionally, the nonsignificant difference between the Spanish and Boer breeds could result from the low sample size and the elevated susceptibility of the one intact male used in this study (Gamble and Zajac, 1992; Shakya et al., 2009).

During this study, Goat B, a Boer goat, was the only adult goat that received multiple doses of anthelmintics, indicating his FEC was over the critical limits on numerous occasions (Machen et al., 2017). As a result, it is believed that his FEC is misrepresented in this study since the anthelmintic treatments reduced his FEC on multiple occasions. In addition, the other two Boer breed goats had low FEC, decreasing the breed's mean FEC. Moreover, the low sample number for the Boer breed could under-emphasize the variation between breeds. Finally, Goat B is the only goat to reach 8-yr of age, which could also reduce the significance of age on FEC in this study since FEC tends to increase after the age of 2-yr (Wang et al., 2017).

The results of this study indicate that FEC measures are best described using the ZINB distribution since they tend to be aggregated, and the zero-frequency class is contaminated with samples that are not part of the infection process. Furthermore, the results indicate that breed significantly impacts a goat's FEC, as does the collection month. Using the results of this study and the techniques mentioned above, a producer can reduce the devastating effects of parasitic nematode infections and anthelmintic resistance.

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