INFLUENCE OF FLOCK SIZE ON ANNUAL GENETIC GAIN FOR SELECTED WEIGHT TRAITS AND INBREEDING IN PURE BARBADOS BLACKBELLY FLOCKS AND THE IMPACT OF GENETIC MAKE-UP WHEN PRODUCING CROSSBREED KATAHDIN AND BARBADOS BLACKBELLY RAMS ON A GOVERNMENT OPERATED NUCLEUS FARM.

A thesis presented in partial fulfilment of the requirement for the degree

MASTER OF ANIMAL SCIENCE

Massey University, Palmerston North

New Zealand

Anthony Cyrille

2021

Abstract

In developing countries, an interest by governments and farmers in improving production by using genetic gain in indigenous animals and utilizing the benefits of crossbreeding exists. This has been plagued by poor genetic improvement and high rates of inbreeding when these decisions have been left solely to the farmer. As a result, nucleus breeding schemes that are centrally located or are linked with village-based nucleus schemes have served as viable options to address the deficiencies of village level management of genetic improvement. In the tropics, particularly the Latin America and Caribbean region, (LAC), producers are beginning to realize the benefits of crossbreeding and the introduction of exotic breed genetics into their tropical hair sheep flocks is increasing, though there introduction has low levels of success and not very sustainable in the long term.

This study was carried out to determine appropriate systems to improve the sheep breeding program at the government operated Central Livestock Farm (CLF), in the Caribbean Island of Dominica. To achieve this, three aspects were addressed, firstly methods to increase the rate of annual genetic gain, secondly to consider the annual rate of inbreeding within the indigenous Barbados Blackbelly breed and finally to investigate production of crossbreed rams from exotic and indigenous breeds.

This study initially focused on the evaluation of pure breeding schemes for a nucleus flock of varying population sizes using the Barbados Blackbelly. Pure breeding schemes were simulated for a nucleus that consisted of either 50 or 100 ewes, each with five or ten rams respectively. These breeding schemes were evaluated based on annual rate of genetic gain for birth weight (BW), weaning weight (WW) and average daily gain (ADG) for different scenarios: age, selection intensity and accuracy of selection. The mating strategy to produce crossbreed rams also involved the Barbados Blackbelly as well as the Katahdin. The effect on a nucleus herd when producing crossbreed rams of different genetic makeup was considered.

The results of the present study indicated that annual rate of genetic gain for BW, WW and ADG when changes are made in generation interval, selection intensity and accuracy of selection was always greater when accuracy of selection was done objectively compared to subjectively. Overall, the 100 ewe, five rams breeding flock when analysed objectively had the greatest annual rate of genetic gain. Inbreeding coefficient was greater in breeding schemes with five rams; however, these rates were still acceptable because they were at the recommended rate of < 1%. It is also important to note that when simulations were done in 50 ewe, five rams self-replacing flocks meant to produce crossbreed rams, the rate of inbreeding was > 1%. Production of crossbreed composite rams was quicker than producing upgraded rams, four and six years respectively and conversion of ewe flock from pure to crossbreed also occurred quicker in composite ram production. Additionally, the production of crossbreed composite rams produced the most rams during the period of study, when no replacements was considered the number of rams produced was 58 and 12 respectively, and in self-replacing flocks, 43 and nine respectively.

This study suggests that the most appropriate nucleus flock size would be a 50 ewe, five rams flock because of the limitations due to space at the at the CLF. The CLF should also concentrate on producing the crossbreed composite male and not incorporate self-replacement as a component of its crossbreeding program.

Acknowledgements

Firstly, I would like to acknowledge and thank the government and the people of New Zealand who through the Ministry of Foreign Affairs and Trade (MFAT) for awarding me a New Zealand Development (NZAID) Scholarship as well as the International Student Support Office (ISSO) of Massey University for ensuring my stay in New Zealand was as comfortable as possible, especially during this time of Covid-19.

This document and the research to complete it would not have been possible had it not been for the incomparable support of my advisor, Professor Hugh Blair. His professionalism, knowledge and attention to detail has been the main reason I was able to stay on track and focused and see this journey through completion. I think from my first encounter with Hugh, he knew exactly what I wanted to achieve and guided me in materialising that vision. From the very first draft to this final document he has answered questions, provided guidance, and always ensured that “we will finish on time”. I also want to thank Professors Paul Kenyon, Patrick Morell, Nicolas Lopez-Villalobos, Dave Thomas, and Dr. Rene Corner-Thomas for the support given which created a very conducive environment for learning.

To the Caribbean students at Massey University, my colleagues in the master’s office and other friends in “Palmy” your support was greatly appreciated and will not go unforgotten. To my mother, brothers and sister and all other family members and friends who, though being a world away stayed in constant contact and ensured I was always doing okay, those video calls meant a great deal.

In closing, I want to say that this accomplishment, this degree, is as much yours as it is mine, Thank you.

Dedicated to my daughter, Regina Chaeli “Queen of Heaven”

Table of contents

Contents

List of Tables

List of Figures

List of Abbreviations

$\bar{i}$	Selection Intensity
ΔF	Rate of inbreeding
ΔG	Genetic gain
ADG	Average daily gain
BB	Barbados Blackbelly
BW	Birth weight
CLF	Central Livestock Farm
FAO	Food and Agricultural Organization
L	Generation Interval
LAC	Latin America and Caribbean
r_{TI}	Accuracy of selection
WW	Weaning weight

Introduction

Across all agricultural producing regions worldwide, small ruminants, sheep and goats, are considered foremost contributors to livestock production (Notter, 2012). Due to their shorter production cycles, quicker time to market and minimal investment, they play a significant role relative to large ruminants in smallholder agriculture (Tibbo et al., 2006). In contrast to lager commercial operations, economic gain is not the main priority for keeping animals for smallholders, but instead, the animals are kept for family needs (Kosgey et al., 2006). However, prospects to increase production has arisen due to global demand for red meat, even though increased production requires additional inputs such as food, labour and management (Notter, 2012). Nevertheless, efforts to create programs that improve small ruminant production in developing countries have been shown to have constraints, with low productivity of animals cited as a major concern (Tibbo et al., 2006).

Animal productivity can be improved genetically by following three approaches : (i) selection between breeds (ii) selection within breeds and (iii) crossbreeding (Kosgey et al., 2006; Tibbo et al., 2006). Crossbreeding has been used in sheep to increase performance in traits which are deemed important to the livestock producer. Sheep are primarily used for meat, wool, and milk. However, it is unlikely that one breed can meet all the demands required, particularly because of the origin of the animal and its intended use by the producer. Sheep breeds are acclimatized to the environments in which they were developed, and this influences the traits in which they are superior relative to breeds developed in different environments (Leymaster, 2002). In the tropics, particularly the Latin America and Caribbean region, (LAC), producers are beginning to realize the benefits of crossbreeding and the introduction of exotic breed genetics into their tropical hair sheep flocks is increasing. Though a common practice in the tropics, introduction of temperate breed genetics into indigenous flocks have low levels of success and have not been very sustainable in the long term (Kosgey et al., 2006).

Tropical hair sheep are hardy animals that possess the ability to reproduce throughout the year, tolerate heavy parasite loads in either wet and humid or arid and dry conditions, but they typically have poor growth rates (Hinojosa-Cuellar et al., 2011a) and carcass quality (Getachew et al., 2016). Exotics, usually breeds from areas with temperate pasture growing conditions, originating from latitudes 35-55° N in Europe and the Near East (Zygoyiannis, 2006) have higher average daily gains and possess superior carcass quality (Leymaster, 2002) but are less tolerant to parasitic infestations and tropical climatic conditions (Bishop, 2012; Bowdridge et al., 2013).

Crossbreeding, especially breeds from two different environments, may improve the productive potential of the offspring because of the effects of heterosis (Leymaster, 2002). Numerous composite breeds have been generated using crossbreeding done over time, in 68 countries, over 443 composite breeds have been developed (Shrestha, 2005). Two examples of successful composite breeds which have been used extensively in the LAC are the Katahdin, which was developed by crossbreeding Suffolk, Wiltshire Horn and Virgin Island White breeds (Rasali et al., 2006) and the Dorper was developed from crossing the Dorset Horn and Blackhead Persian(de Waal & Combrinck, 2000; Milne, 2000).

This thesis will explore the concerns of indigenous breed improvement, in this case the Barbados Blackbelly, and the production of crossbreed rams, Katahdin and Barbados Blackbelly, on a government owned and operated livestock breeding station on the Caribbean island of Dominica. The literature review chapter will evaluate genetic improvement and crossbreeding of sheep in the Latin America and Caribbean (LAC) region and other territories and countries with similar growing conditions, namely Africa and Asia. Improving the ability of nucleus farms in developing countries to produce animals of improved genetic quality only serves in increasing the productivity and profitability to the producers involved in the sheep industry.

2. Literature Review

2.1. Introduction

An interest by governments and farmers in improving production by using genetic gain in indigenous animals and harnessing the benefits of crossbreeding still exists in developing countries. However poor genetic improvement and high rates of inbreeding have been documented when genetic improvement is implemented at the village level (Gizaw et al., 2009). This is due to poor selection, coupled with small population size, minimal record keeping and low animal performance (Gandini et al., 2014). As a result, nucleus breeding schemes that are centrally located or are linked with village-based nucleus schemes have served as viable options to address the deficiencies of village level management of genetic improvement. This literature review will evaluate crossbreeding of sheep, particularly in the LAC, and the role of nucleus breeding schemes with the intention to identify strategies that will guide future crossbreeding schemes without the loss of indigenous breeds.

2.2. Overview of Latin America and Caribbean Region

Domesticated animals first arrived in the Americas in 1493 on Christopher Columbus' second voyage. These animals landed on the island that is now modern day Haiti and Dominican Republic, after which they were distributed throughout the islands and the continent (McManus et al., 2010). Various species were introduced following colonization and over time these animals through the process of natural selection developed traits such as hardiness, prolificacy and resistance to diseases and endo- and ecto parasites (Carneiro et al., 2010). At present, the contrasting production systems of developed and developing countries are the two distinct categories of the global livestock sector (Thornton, 2010), the latter of which the majority of the LAC countries belong to. The LAC is made up of three subgroups, namely, South America, Central America and the Caribbean, Table 1 indicates the countries which makes up each subgroup.

Table 1. Subgroupings and Countries of the LAC (FAO, 2014)

Subgroup	Countries
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Falkland Islands, French Guiana, Guyana, Paraguay, Peru, Surinam, Uruguay, Venezuela
Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua
Caribbean	Antigua & Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cuba, Dominica, Dominica Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Netherland Antilles, Puerto Rico, St. Kitts and Nevis St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago United States Virgin Islands

Crop production has experienced drastic drops within the Caribbean states over the past decades, however, significant increases have been observed in livestock production (FAO, 2016). Despite the gains, the sector is still underdeveloped and dominated by small farming, primarily producing small ruminants (Graham, 2012). This is due to their ability to convert farm waste and fodder into food, their prolificacy, and their adaptability to scrub land. Sheep and goats have successfully become a part of the small holder farming system in the Caribbean and contribute significantly to farm income (FAO, 2016).

Small holder farming has also been a reason why sheep numbers have not increased in numbers compared to other livestock species in Brazil (McManus et al., 2010), while Mexico on the other hand , has witnessed marked increases over the last decade, with sheep numbers increasing approximately 20% (Munoz-Osorio et al., 2016). Methods of production of sheep are varied, and include extensive, semi-intensive and intensive systems (Munoz-Osorio et al., 2016) which are very dependent on land availability. In the Caribbean, pastures and meadows make up 40.1 % of permanently occupied land, whereas in the South and Central America the percentages were 76.2% and 70%, respectively (FAO, 2014).

In 2012 the global sheep population was 1.2 billion, with the LAC comprising of 7 % of that total , the greatest populations being in Brazil and Mexico (FAO, 2015). Figures 1,2,3 and 4 indicates sheep population by subgrouping and country.

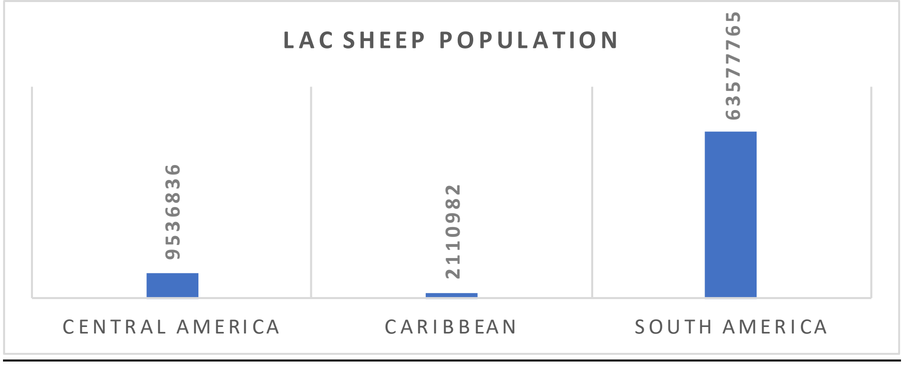


Figure 1. Sheep population in the LAC (FAO, 2015)

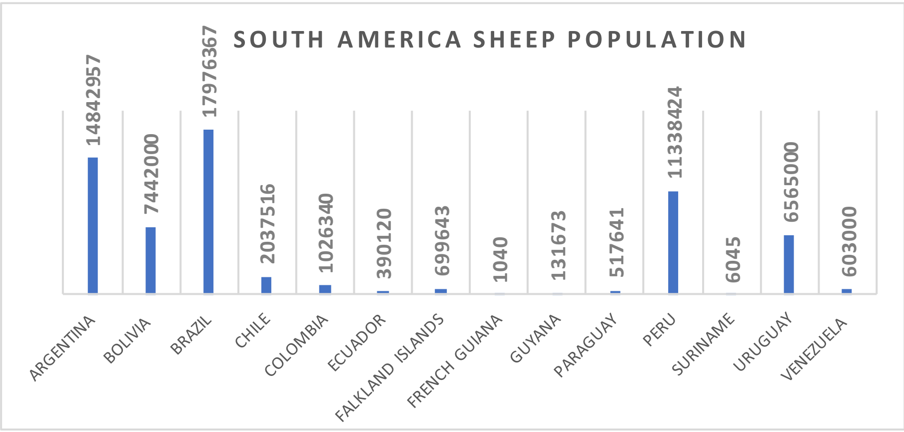


Figure 2. Sheep population in South America (FAO, 2015)

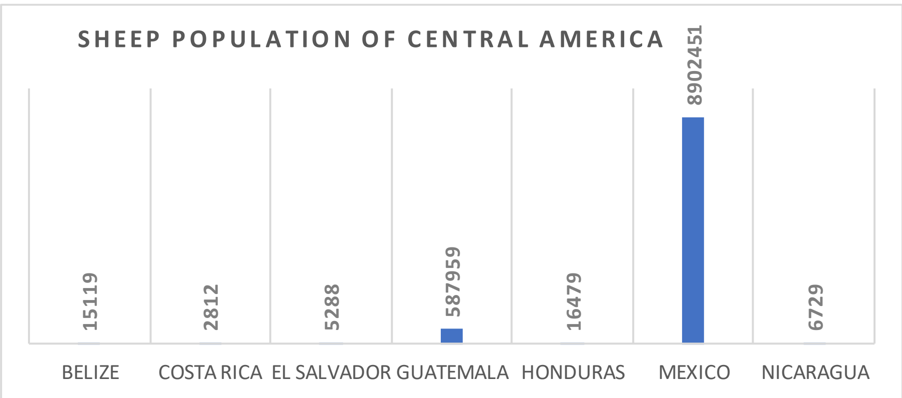


Figure 3. Sheep Population in Central America (FAO, 2015)

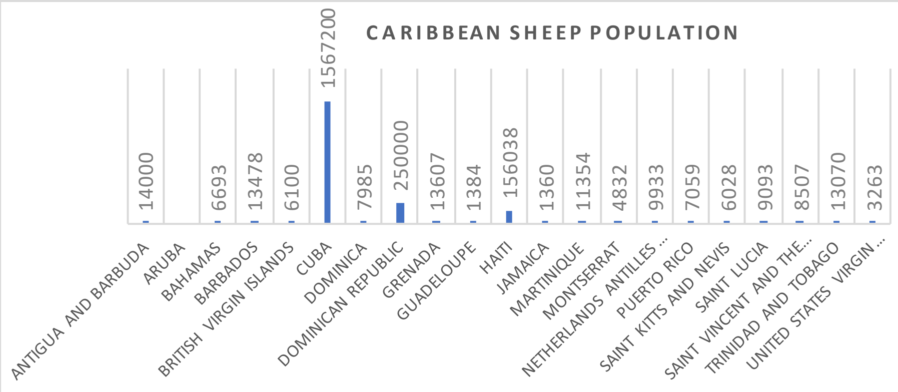


Figure 4. Sheep population in the Caribbean (FAO, 2015)

Traditionally, indigenous sheep breeds were the primary breeds utilised for both their cultural and economic values, Table 2 lists a few of the more prominent indigenous breeds in the LAC. However, in South America, this scenario is changing as the introduction of more productive (temperate) exotic breeds have been introduced in the 20th century (Carneiro et al., 2010)

Table 2. Some indigenous sheep breeds in the LAC region

Breed	Country	Attribute	Reference
Barbados Black belly	Caribbean (Barbados)	Prolific	de Almeida (2018)
Criollo	Andean (Central American)	Resistance to gastro-intestinal parasites	Romero-Escobedo et al. (2016)
Martinik Hair Sheep	Caribbean (French West Indies)	Utilization of tropical forage	Archimède et al. (2008)
St. Croix	Caribbean (USVI)	Resistance to gastro-intestinal parasites	Burke and Miller (2004)
Pelibuey	Mexico	Reproductive activity	(Macias-Cruz, 2009) (Arroyo et al., 2007)
Mora Novada	Brazil	Adaptability to semi-arid conditions High quality meat and skin	Souza et al. (2013)

Retrieved from (Kosgey et al., 2006)

Within the LAC region, 51 breeds of local sheep have been reported(FAO, 2015). Brazil has been documented as having the most hair sheep in the region (Carneiro et al., 2010), with 27 breeds or ecotypes, with only 11 seeing increased use while new breeds are continuously being imported (McManus et al., 2010). Imported breeds are also used extensively in the

Caribbean (Graham, 2012), Chile, Ecuador and Paraguay (FAO, 2015) and Mexico (Munoz-Osorio et al., 2016) in cross breeding programs in an effort to increase production (FAO, 2015). Because of their temperate origin, these breeds are not as adapted as the naturalized/indigenous breeds (Carneiro et al., 2010), which are typically hair type, such as the Santa Ines, Morada Nova, Somali from Brazil (McManus et al., 2010), Pelibuey from Mexico (Munoz-Osorio et al., 2016) and Barbados Blackbelly from Barbados (de Almeida, 2018). The introduction of new more productive temperate breeds has even resulted in some naturalized breeds becoming extinct (Carneiro et al., 2010), as well as development of new composites (Table 3).

Table 3. Composite sheep breeds, country of origin, year developed and parental breeds

Composite	Country of origin	Year	Parental breeds
Asblack	Peru	1990	Assaf, Barbados Blackbelly Corriedale
Argentine Cormo	Argentina	1979	Cormo, Peppin Merino, Polled Merino, Corriedale
Argentine Merino	Argentina	1875-1990	Criollo, Spanish and Saxony Merinos, Rambouillet
Brazilian Somali	Brazil		Blackhead Persian, Local
Brazilian Wool less	Brazil		West African, Criollo
Corino	Argentina	1970	Merino, Corriedale
Merlin	Uruguay	1910	Rambouillet (75%), Lincoln (25%)
Rabo Largo	Brazil		Short hair, Wool less, Fat-tailed breed of South Africa, Criollo
Santa Ines	Brazil	Late 1940’s	Bergamasca, Brazilian wool less
Tarset	Mexico		Pelibuey, Dorset

Retrieved from (Rasali et al., 2006)

2.3. Heterosis

The exploitation of heterosis or hybrid vigour is one of the main reasons for crossbreeding. Heterosis is how much more productive the first cross (F1) offspring are compared to the average of the parent breeds (Kaeppler, 2012; Kumar et al., 2016; Petrović et al., 2009).

The percentage of heterosis is measured as:

% Heterosis = [(average of reciprocal cross –average of two parent breeds) ÷ average of two parent breeds] x 100

Heterosis retention is dependent on the type of cross and genetic makeup of the offspring (Table 5) and can be estimated for various production traits (Table 4).

Table 4. Estimates of lamb and ewe heterosis effects expressed as a percentage of the purebred average.

Trait	Lamb	Ewe
Birth weight	3.2	5.1
Weaning weight	5.0	6.3
Preweaning daily gain	5.3	-
Postweaning daily gain	6.6	-
Yearling daily weight	5.2	5.0
Conception weight	2.6	8.7
Lambing rate	2.8	3.2
Preweaning survival	9.8	2.7
Lambs born per ewe exposed	5.3	11.5
Lambs weaned per ewe exposed	15.2	14.7
Litter weaning weight per ewe exposed	17.8	18.0

Retrieved from (Leymaster, 2002)

The additive component of low heritable traits is small, usually less than 10%, therefore, these traits, such as reproduction, survival and overall fitness, profit from heterosis the greatest (Kumar et al., 2016; Spangler, 2007). On the other hand, high heritable traits such as meat quality (Mortimer et al., 2010), exhibit little or no heterosis (Wakchaure et al., 2015).

Table 5. Fraction of heterosis (h)expected for alternative systems of breed use

Mating System		Heterosis		
		h^I	h^M	h^P
2-breed cross	F_1 A♂ x B♀	1	0	0
3-breed cross	C♂ x A-B♀	1	1	0
	A-B♂ x C♀	1	0	1
4-breed cross	C-D♂ x A-B♀1	1	1	1
Rotation crossing	2 sire breeds	1/3	2/3	0
	3 sire breeds	6/7	6/7	0
	4 sire breeds	14/15	14/15	0
C♂ x Rotation ♀	2 dam breeds	1	2/3	0
	3 dam breeds	1	6/7	0
	4 dam breeds	1	14/15	0
Composite[a]	2 breed	1/2	1/2	1/2
	3 breed	2/3	2/3	2/3
	4 breed	3/4	3/4	3/4

[a] Equal percentage of each breed, h^I = Individual heterosis, h^M= Maternal heterosis, h^P=Paternal Heterosis

Retrieved from(Dickerson, 1973)

Heterosis can be expressed at three stages:

I. Individual heterosis, which is the improvement in performance of the crossbred in contrast to that of its parent, an example being weaning weight (Kumar et al., 2016; Wakchaure et al., 2015).

II. Maternal heterosis, which are the benefits of the crossbred mother relative to the pure-bred mother, whereby offspring will show improvements in performance because of increased milk production and improved mothering environment (Kumar et al., 2016; Spangler, 2007).

III. Paternal heterosis, is defined as the advantages that are obtained when using a crossbred sire. The individual and maternal heterosis and breed complementarity benefits from having crossbred lambs and ewes are well established (Muñoz-Osorio et al., 2018; Notter et al., 2017). However, the benefits attributed to crossbred or composite rams on flock improvement is less well studied (Leymaster, 1987; Notter, 1987) such as age of puberty being reduced (Kridli et al., 2016), improved scrotal circumference, libido and sperm concentration

(Spangler, 2007; Wakchaure et al., 2015). Kridli et al. (2010) observed the mounting frequency in crossbred Awassi ram lambs was higher than pure Awassi ram lambs, and their reproductive parameters were improved. By utilizing younger males in a breeding program genetic gain and financial returns can be achieved quicker (Price et al., 1991).

Crosses between tropical and temperate breeds display large amounts of heterosis (Wakchaure et al., 2015) as well as good breed complementarity between traits, and may result in animals that display increased performance (Leroy et al., 2016). Whereas, with within breed genetic gain, additive gene action is equal to the mean of the breeds involved (Leroy et al., 2016), additive gene action makes no contribution to heterosis (Dubey et al., 2019). Instead, heterosis is the consequence of overdominance, and occurs because the heterozygote is superior over both homozygous genotypes, possibly due to a third protein when two alleles are present (Kaeppler, 2012; Kumar et al., 2016) and two different types of non-additive gene action (1) dominance effects, that are expressed by the individual gene pairs ; and (2) epistasis, inter-allelic interactions between genes at one loci with one or more loci (Kumar et al., 2016).

2.4. Crossbreeding

Crossbreeding is the mating of ewes and rams from different breeds, and is often used with the intention of increasing productivity and consequently farm profitability (Buckley et al., 2014; Leymaster, 2002; Sousa et al., 2011). Early livestock breeding techniques were modelled on the practises employed by plant breeders in the production of hybrid corn, however, inbreeding was not useful for livestock species due to marked losses in productivity and increased vulnerability to diseases (Shrestha & Fahmy, 2007). The utilisation of crossbreeding in sheep has now become common practice with the outcomes being improved overall performance in targeted traits from the parent breeds and exploitation of the non-additive genetic variance to generate heterosis (Yadav et al., 2018).

In developing territories, the use of crossbreeding is one of the most common (Mbuku et al., 2015) and quickest methods (Ayichew, 2019) to implement genetic improvement of indigenous stock. Crossbreeding also allows for more efficient use of land resources (Fogarty,

2006) because relative to pure-breeds, crossbreeds can perform better, including improved efficiency in particular environments (Leymaster, 2002; Mbuku et al., 2015).

The advantages of crossbreeding can therefore be categorized as heterosis, breed complementarity and reversal of the negative effects of inbreeding (Buckley et al., 2014; Cloete, 2012; Petrović et al., 2009; Yadav et al., 2018). Various forms of systematic crossbreeding can be used to achieve this (Table 6). Additionally pure breeding systems can be mentioned because they produce replacements and can be used as the average in assessing the productivity of the crossbreds (Leymaster, 2002) . Crossbreeding can lead to recombination losses, which result from the loss of desirable gene combinations stored in the parent breeds (Wakchaure et al., 2015). This does not affect first cross animals, because the significant gene combinations are unbroken, however, in following generations, crossing over between chromosomes from the different parent breeds can result in the progressive loss of those favourable gene combinations (Cassell & McAllister, 2009).

Table 6. Mating types and products realized in general purpose crossbreeding systems.

Genetic type of lamb	Mating type[a]	Products[b]
Purebred	A x A	Replacement, market
First cross	A x A	Replacement, market
	A x B	Market
Rotation		
Two breed	AB_R	Replacement, market
	BA_R	Replacement, market
Three-breed	ABC_R	Replacement, market
	BCA_R	Replacement, market
	CAB_R	Replacement, market
Composite		
Two-breed	AB_C	Replacement, market
Three-breed	ABC_C	Replacement, market
Four-breed	$ABCD_C$	Replacement, market

[a] A, B, C, and D represent breeds, subscripts R and C indicate rotation and composite, respectively.

[b] Products of matings are replacement ewes and market lambs.

Retrieved from (Leymaster, 2002).

2.4.1 Crossbreeding Systems

The following are brief descriptions of some of the systematic forms of crossbreeding, more detail is available in Mishra et al. (2017) and Leymaster (2002).

2.4.1.1 First Cross or F1:

This is the first stage of any crossbreeding program which utilizes only one breed of ewe (A) which are bred to rams of the other breed (B) (Yadav et al., 2018). Offspring from this breeding obtain 50% of their genes from each parent breed and has the benefit of 100% individual heterosis (Leymaster, 2002; Yadav et al., 2018) (Table 5). In relation to pure bred flocks, Leymaster (2002) stated first cross lamb heterosis can increase meat production up to 17%. To maintain this system of crossbreeding, either a proportion of ewes must be mated to rams of breed A to produce replacement ewes, or replacement ewes must be purchased from outside the flock (Leymaster, 2002).

2.4.1.2 Rotational:

A breeding system that most commonly uses two or three breeds of rams in rotation in successive generations (Leymaster, 2002; Mbuku et al., 2015; Yadav et al., 2018). In a two breed rotational program, individual lamb and maternal heterosis will average 67% after a few generations; if a third breed is included it rises to 86% (Leymaster, 2002; Yadav et al., 2018). Pure-bred rams are used in rotational systems (Shrestha & Fahmy, 2007). Rotational crossbreeding also has the advantage of producing crossbred ewes as replacements (Leroy et al., 2016).

2.4.1.3 Composite:

Composite systems presents a much simpler breeding structure than the rotational system and the foundation of composite breeds are based on crosses among two or more breeds (Leymaster, 2002; Shrestha & Fahmy, 2007). The succeeding generations are products of crossbred parents and they benefit from individual lamb and maternal heterosis as well as paternal heterosis effects such as ram fertility and libido (Leymaster, 2002) (Table 5). Unlike rotational systems, composite systems produce animals which have a stable breed composition and does not require the purchase of new animals (Shrestha & Fahmy, 2007).

2.4.1.4 Terminal:

In a terminal crossbreeding system pure, first-cross, rotational or composite bred ewes are mated to rams of specific sire breeds to produce market lambs that exhibit 100% individual lamb heterosis (Leymaster, 2002; Yadav et al., 2018). Unlike the other cross breeding systems which utilize both genetic effects of breed diversity and heterosis, terminal crossbreeding systems also exploits complementarity (Leymaster, 2002).

2.4.1.5 Grading up:

In developing countries, offspring from two breed crosses utilizing exotic breeds are often perceived to be more productive (Shrestha & Fahmy, 2007) leading to a common practice of grading-up or repeated mating to the exotic breed (Mbuku et al., 2015). Grading up usually utilizes only the male of the new breed (Kosgey et al., 2006), and has led to loss of the important attributes of the indigenous breed and the unintentional formation of composite breeds (Shrestha & Fahmy, 2007). Grading up is best suited for nucleus flocks that produce breeding stock unlike the less complicated first or terminal crosses which can be carried out by the commercial producers (Gizaw et al., 2014b). As a result, Cloete (2012) stated that, in developing countries, studies must be carried out with breed introductions so that both improved production and indigenous resource conservation can occur seamlessly.

2.5. Breed Complementarity

Breed complementarity is another benefit of crossbreeding. Two or more breeds of differing morphological features and production performance can be combined and provide benefit, without the benefit of heterosis (Rasali et al., 2006). It occurs because of additive gene action (Yadav et al., 2018) whereby the strengths of one breed compensate the weakness of the other (Petrović et al., 2009; Yadav et al., 2018). To exploit the benefits of breed complementarity the breeds that are matched must excel in dissimilar aspects (Spangler, 2007), such as growth rate and carcass composition with climate, feed resources, fertility, disease resistance and market preference (Garcia et al., 2019), that are essential to production goals. Leymaster (2002) also underscored the importance of reciprocity in mating of the two breeds (ewe A to ram B and ewe B to ram A) and to consider how that will affect production costs and productivity. Under tropical conditions, breed complementarity is most often utilised in crossbreeding schemes using quick growing sires as a means of improving production systems quickly (Blasco et al., 2019; Paim et al., 2019; Vargas Junior et al., 2014).

2.6. Performance of Barbados Blackbelly and Katahdin

Blackbelly sheep breed year-round in the tropics. Rainfall and access to forage being the main influences to breeding seasons instead of photoperiod (Wildeus, 2011). Breeding season has a significant effect on birth weight but not on daily gain, pre weaning and weaning weight (Avril et al., 2011). Table 7 shows the average number of lambs born per ewe from a number of studies. The average lambs born per ewe ranged from 1.37 (Galina et al., 1996) to 1.90 (Rastogi, 2001) with ewes having fertility rates greater than 90% (Knights et al., 2012). Information on ewe fecundity based on age was not current, however earlier studies carried out in Barbados indicated that fecundity in one-and two-year old ewes was 1.5 and 1.7, respectively (Nurse et al., 1983) and for 1st and 2nd lambing ewes, litter size was 1.45 and 1.89, respectively (Bradford et al., 1983). Multiple birth types comprised the greater percentage , with single 36.7%, twin 57.0%, triplet 4.4%, quadruplet 1.9% reported by Solomon et al. (2006) and single 34.8%, twin 46.9%, 15.8% triplet, quadruplet 2.1%, and quintuplet 0.4% reported by (Bradford et al., 1983). As shown in Table 7, lamb mortality ranged from 5.6 % (Gatenby et al., 1996) to 23% (Segura et al., 1996).

Table 7. Number of lambs born and lamb mortality of Blackbelly ewes.

Number of lambs born	Mortality (%)	Reference
1.86	10.9[a]	Bradford et al. (1983)
1.37	17.0[a]	Galina et al. (1996)
1.54	5.6[b]	Gatenby et al. (1996)
1.67	23.8[b]	Segura et al. (1996)
1.90	18.3[a]	Rastogi (2001)

[a] average mortality, [b] preweaning mortality

Blackbelly ewes overall have been reported as a breed with one of the shortest lambing intervals (245 days) compared to Pelibuey (255 days), and Dorper (257 days) and Katahdin (260 days) (Nasrat et al., 2016). Regardless of ewes being pre-weaned, temporarily weaned at ram introduction or continuous suckling, they still displayed high reproductive performance with a lambing interval under nine months (Knights et al., 2012). Similar lambing intervals have also been recorded in other studies (Bradford et al., 1983; Galina et al., 1996). For first parity ewes, the mean age for lambing was similar in studies reviewed, 467 days (Bradford et al., 1983) and 480 days (Galina et al., 1996).

Birth weight was similar across most studies, with a range of 2.5 kg to 3.22 kg, although it varied with litter size. Table 8 shows the average birth weights by litter sizes from the various studies as well as average daily gains and weaning weights. Late weaned lambs had greater daily gain, weaning and final weights (Knights et al., 2012). Pelibuey and Composite lambs (Blackbelly x Pelibuey ewes mated with Katahdin or Dorper rams) had greater daily gains than pure Blackbelly lambs, 108g, 110g, and 95g respectively and also weaning weights, 12.7 kg, 12. 8 kg 11.6 kg (Hinojosa-Cuellar et al., 2011b).

Table 8. Overall birth weight and birth weight based on litter size, average daily gain and weaning weight of Blackbelly lambs

Birth Weight (kg)				Average Daily Gain (g)	Weaning Weight (Kg)	Reference
Litter Size						
average	1	2	3			
2.71	3.22	2.73	2.28	115.30	11.69	Avril et al. (2011)
		2.99	2.75			Solomon et al. (2006)
2.7	3.1	2.5		122[c] 88[d]	13.7[e]	González Garduño et al. (2002)
2.75				152	16.7	Rastogi (2001)
2.9				115	14.8	González-Domínguez et al. (2016)
2.85						Galina et al. (1996)
				98-107 [a] 118-124[b]		Knights et al. (2012)

[a] early weaned lambs, [b] late weaned lambs, [c] pre-weaning ADG, [d] post weaning ADG, [e] adjusted at 90 days

Tropical breeds are known to produce less milk than temperate breeds (Haenlein, 2007). Daily milk production of temperate breeds such as Friesian (Park & Haenlein, 2006) and Lacaune (Barillet et al., 2001) are higher than that of topical hair breeds(Burgos-Gonzalez et al., 2018), since tropical hair breeds primary purpose is meat (Godfrey et al., 1997). Though highly adapted to the tropical environment, milk production in tropical breeds may still be influenced by heat stress (Godfrey et al., 1997). Milk production in heat stressed ewes compared to non-heat stressed ewes when exposed to constant temperatures of 35°C decreased during late pregnancy and early lactation (Abdalla et al., 1993). In a milk production study, Katahdin ewes did not differ in milk produced per day compared to the St. Croix White, a Caribbean hair sheep, 1.38 L/day and 1.26 L/day, respectively (Burgos-Gonzalez et al., 2018). Similarly, the Ovine Martinik, a Caribbean hair sheep similar to the Blackbelly, selected to increase productivity and internal parasite tolerance (de Almeida, 2018), had an average milk production of 1.2 L/day (Ortega-Jimenez et al., 2005). These studies indicate that levels of milk production amongst hair sheep is similar. It has also been reported by Godfrey et al. (1997), that hair sheep milk production decreased over a 63-day lactation period, whereas a native Florida wool breed had a flatter lactation curve with little decrease during that same period.

The Katahdin was developed in the United States (Rasali et al., 2006) and introduced into Mexico in the 2000's (Sanchez-Davila et al., 2015) particularly to be used in crossbreeding (Macías-Cruz, 2012). In observing genotype effect, it is found that pure bred Katahdin and their crossbred offspring had greater litter and weaning weights and average daily gain than tropical hair sheep breeds from the Latin America and Caribbean region (LAC) (Table 9).

Table 9. Birth weight (BW), weaning weight (WW) and average daily gain (ADG) of Katahdin, Blackbelly and Pelibuey breeds and their crosses

Breed	BW (kg)	WW (kg)	ADG (g)	Reference
K x K	3.0	19.2	235.7	Burke et al. (2003)
K x Pb P x Pb	5.02 5.55	26.29 31.37		Macias-Cruz (2009)
K x BB K x Pb Pb x BB Pb x Pb	2.70 2.90 2.70 2.60	11.20 12.30 10.40 19.20	95 104 85 93	Rios-Utrera (2014)
K x BB BB x BB	5.42 5.76	20.69 22.35		Nasrat et al. (2016)
K x K Pb x Pb	3.95 3.27	11.28 10.7	130 130	Chay-Canul et al. (2019)

K=Katahdin, Pb=Pelibuey, BB=Katahdin

In this study, Barbados Blackbelly sheep, which are widely distributed throughout the LAC (de Almeida, 2018), will be selected for relevant traits such as birth weight, weaning weight and average daily gain. The genetic composition of the crossbred rams would be Katahdin and Barbados Blackbelly. Very few studies have been done observing crossbreeding between Katahdin and Blackbelly breeds. However Rios-Utrera (2014)stated that offspring of Katahdin crossed with tropical hair sheep have increased daily gain.

The importance and benefits of tropical hair sheep to small holders are well documented (Hinojosa-Cuellar et al., 2011a). However, limitations in growth and carcass quality (Getachew et al., 2016) has led to crossbreeding with imported breeds because of their ability to increase productivity (Muñoz-Osorio et al., 2018). Unplanned crossbreeding ,particularly grading up, is a major cause for loss of the important attributes of indigenous breeds (Shrestha & Fahmy, 2007). Studies related to crossbreeding within the LAC has been carried out, but to date no information has been found with government operated nucleus breeding scheme. This study seeks to address breed improvement in the Barbados Blackbelly as well the production of crossbreed males being made available to farmers through a government operated nucleus breeding scheme.

2.7. Breeding Programs

Successful implementation of genetic improvement programs in small ruminants in developing countries as described by Kosgey et al. (2006) must meet the needs of the farmer, which would be motivated by the target market. In order to achieve this, an organized breeding scheme whether government, private or a collaborative effort between the two entities is required (Kosgey & Okeyo, 2007). Presently, production systems in developing countries are defined by small flock size, shared grazing, lack of pedigree and performance recording and uncontrolled breeding (Gizaw et al., 2009).Uncontrolled breeding, particularly crossbreeding to the indigenous breeds, can result in adaptation traits such as disease resistance, being compromised (Cloete, 2012). Farmers in these production systems are both ram breeders and meat producers, meaning there is only a one-tier breeding structure, rather than the two- or three- tiered structures typically found in developed countries (Gizaw et al., 2009) (Figures 5 and 6). As a result, in the absence of a structured genetic improvement scheme, the ability to attain and monitor genetic gain is difficult (Abraham et al., 2019).

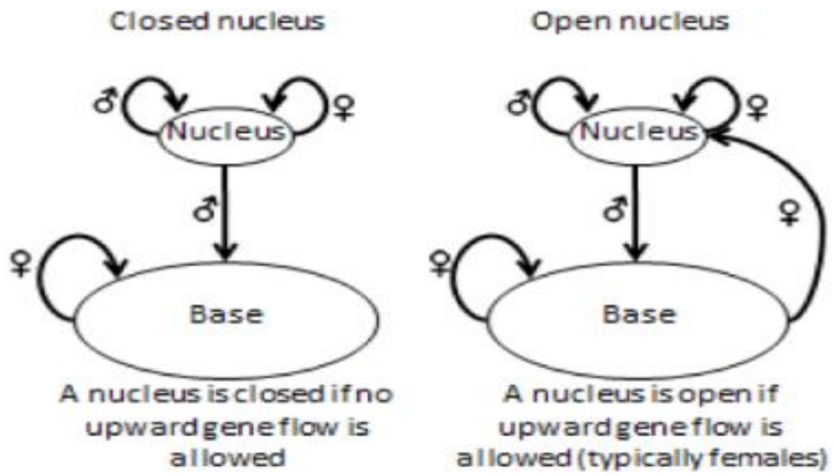


Figure 5. Two tiered closed and open nucleus adapted from (Haile et al., 2020)

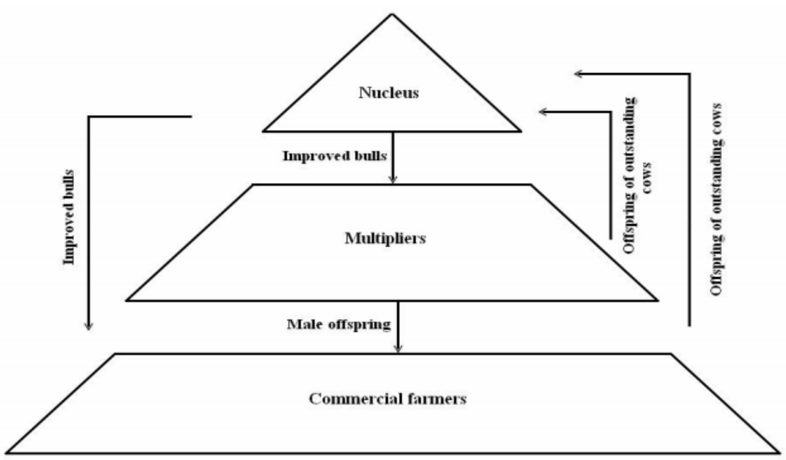


Figure 6. Three tiered open nucleus system adapted from (Bosso, 2006)

When centralized nucleus flocks are utilized as the means for genetic improvement, the improvement in performance should be gradual, from low to medium, rather than low to high. This allows the farmer/producer time to adjust to new managerial decisions attributed to increased gain, as well as time to compare productivity under both nucleus and farmer conditions (Gicheha et al., 2006; Kosgey & Okeyo, 2007). Centralized nucleus flocks require only a small portion of the population to initiate a genetic improvement program (Kosgey et al., 2006), selecting only the animals with superior genetics to be mated to become parents of the following generations (Kosgey & Okeyo, 2007). This system is appropriate because in resource scarce developing countries, the limited funding available can be optimized by focusing it on the smaller populations of the nucleus flock where precise management related to genetic improvement can be executed (Kosgey & Okeyo, 2007). From simulations in small ruminant populations Gandini et al. (2014) reported annual genetic gain from a minimum of 0.073 SD/generation (100- female nucleus for a commercial population of 500 females) to a maximum of 0.138 SD/generation (400-female nucleus for a commercial population of 5,000 females).

A breeding program is identified by two main activities, the selection of animals determined by their estimated breeding values for economically relevant traits in order to generate genetic improvement and secondly, the distribution to the commercial population of the genetically improved animals (Kosgey et al., 2006). Selection within the local breeds takes account the local production systems because it allows for the stability of genetic improvement in productive and adaptation traits (Gandini et al., 2014). The distribution to the commercial population of the genetically improved animals is done through the sires (Gandini et al., 2014; Kosgey et al., 2006). Breeding programs can be enhanced by the use of biotechnology techniques (Gizaw et al., 2014c) particularly artificial insemination, from the sires of the nucleus flocks to increase the number of commercial flocks they serve (Kosgey & Okeyo, 2007).

An alternate design to central nucleus breeding schemes for small holder farming systems is a community-based breeding scheme (Gizaw et al., 2014c). Members within the scheme are assisted by public and private sector organizations, but the decision making and ownership lies with the members, hence their traditional knowledge is incorporated into the overall developmental plan (Mueller et al., 2015). Results from simulations found that higher genetic gains can be attained from the central nucleus schemes(Abraham et al., 2019). However, Gizaw et al. (2009) reported that genetic gain results were comparable in both community and nucleus schemes when mass selection and BLUP selection are implemented. On the other hand, closed flocks in developing countries may be of small sizes which may limit the effectiveness of selection (Kosgey & Okeyo, 2007).

Breeding programs for small ruminants in the tropics vary in design and can be three tiered consisting of a nucleus, multiplier and farmer flock or two tiered consisting of only a nucleus flock and the farmer flock (Kosgey et al., 2006) (Figures 5 and 6). The nucleus flock could either be opened or closed. An open nucleus flock allows for movement of animals of high merit, particularly females, to be moved from the lower tier farmer flock upwards to the nucleus flock (Gandini et al., 2014; Kosgey et al., 2006). Genetic gain is relatively quicker in the open flocks compared to closed ones , about 10-15% quicker(Kosgey et al., 2006) as well as reduced levels of inbreeding (Gandini et al., 2014). In a closed nucleus on the other hand, flow from the lower tier upwards does not exist and though its much simpler to establish and manage, the occurrence of inbreeding is increased and must be monitored and counteracted (Gandini et al., 2014; Kosgey et al., 2006; Kosgey & Okeyo, 2007).

2.8. Flock Structure

Sheep flocks are either one of two production systems. The commercial flock ,which is geared towards meat production, and may have a much older age structure, with ewes as much as ten years old (Abdel-Moneim et al., 2009) and the nucleus flock, which will have a much younger age structure, whose primary interest is in improving genetic gain (van der Werf et al., 2010) . Age structure is critical to genetic gain as is evident in the dairy industry , where it has been reported that the greatest rate of genetic gain was achieved by reducing the generation interval in cows when applying genomic selection (Pryce et al., 2010). The association that exists between age structure and reproductive traits is strong, and thought must be given to decide upon which structure gives optimum returns since they both impact production (Abdel-Moneim et al., 2009). The most productive ages of ewes are between two and six and there is a steady reduction in production beyond that age (Abdel-Moneim et al., 2009; Annett et al., 2011; Ptáček et al., 2017; Yilmaz et al., 2011), (Table 10). Oishi et al. (2008) demonstrated that as the age at which Saanen does were culled increased, there was a decrease in the number of first parity replacement does required, hence the importance and impact of culling age on flock dynamics.

To keep the flock size stable, replacements are selected, the intensity of which will be dependent on ewe lambing rates and number of ewes culled and death rate (Abdel-Moneim et al., 2009). However, intensity may decline with smaller flock sizes (Gizaw et al., 2014d), negatively impacting the rate of genetic gain (Pryce et al., 2010). On the other hand, increasing genetic gain via increasing selection intensity could occur by increasing the male to female ratio (Abdel-Salam et al., 2010) and decreasing the proportion of sires selected (Abdel-Salam et al., 2006).

Table 10. Measurements of pregnancy rate, lambing rate, lambs born, and lambs survived compared to age of ewe.

Ewe age	Measurement				Reference
	Pregnancy rate (%)	Lambing rate (%)	Lambs born per ewe	Lambs born alive per ewe	
2		86.90	1.74	1.60	Ptáček et al. (2017)
3		83.70	1.88	1.70	
4		90.40	1.89	1.75	
5		82.8	1.86	1.76	
>6		81.9	1.80	1.62	
2	48.10	45.60			Yilmaz et al. (2011)
3	70.30	68.80			
4	52.20	49.50			
5	68.20	64.90			
6	60.90	59.50			
7	65.30	57.50			
2			1.49	1.42	Annett et al. (2011)
3			1.62	1.55	
4			1.72	1.64	
5			1.74	1.67	
6			1.65	1.53	

2.9. Conclusion

Early introduction of sheep into the Latin American and Caribbean Region (LAC) lead to the development of highly adaptable indigenous breeds. Recent introductions of more productive exotic sheep breeds have seen the utilization of crossbreeding to capitalize on heterosis, complementarity and breed diversity. The composite Katahdin and indigenous Blackbelly are two breeds which are used extensively throughout the region in crossbreeding programs in an effort to increase production, particularly preweaning. Indiscriminate crossbreeding, however, has resulted in the decline in indigenous populations and overall loss of some indigenous breeds. It is proposed that well-structured nucleus flocks can play a role in limiting these losses, as well as making genetically superior rams to farmers. The design of various breeding structures will be examined in this thesis.

3. Materials and Method

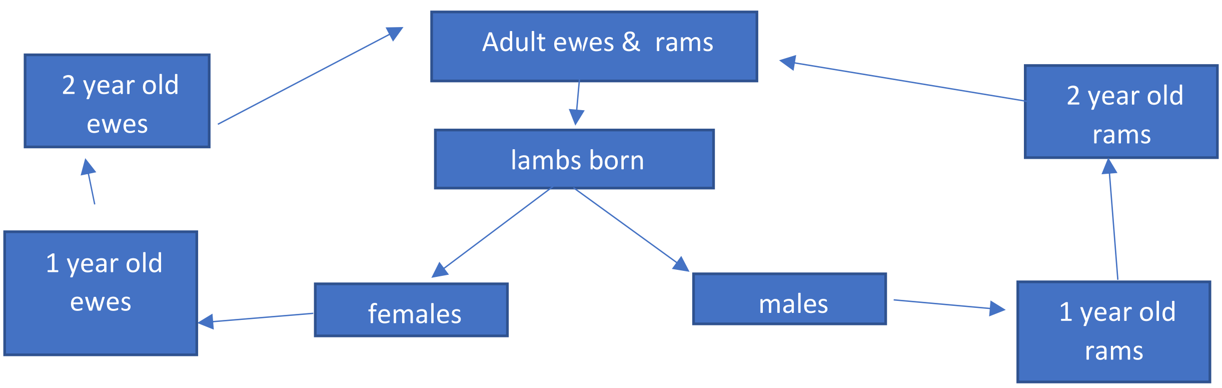
The Central Livestock Farm (CLF) in the Commonwealth of Dominica, West Indies, is located on the north east coast of the island at 15.5 north latitude and 61.3 west longitude at an altitude of 90 ft above sea level. The climate is warm and humid with rains in the summer season. Annual rainfall is approximately 2652.7 mm with peaks between July and November. The maximum and minimum average relative humidity is 79.6% and 71.2%, respectively. The maximum and minimum average temperatures are 30.6°C in June and 22.0°C in February, respectively.

The CLF is approximately 93 acres. Sheep production on the CLF is semi intensive, with a mix of grasses and forages utilizing both grazing and cut and carry feeding methods. The grasses include African Star (*Cynodon plectostachyus*), Pangola (*Digitaria eriantha*), Tanna (*Brachiaria arrecta*) and Elephant (*Pennisetum purpureum*) and forages, mulberry (*Morus alba*), *Gliricida sepium* and *Moringa olifera.* A 2380 ft^2 raised slat floor unit has the capacity to house 75 ewes, with the 2020 ewe count being 49 with an age range of six months to nine years. The sheep on the farm are pure bred (Barbados Blackbelly, Katahdin and West African) and crosses (Barbados Blackbelly x West African, Barbados Blackbelly x Katahdin and Katahdin x West African).

3.1 Nucleus

Pure breeding schemes for Barbados Blackbelly sheep were simulated for a breeding nucleus that consisted of either 50 or 100 ewes, each with five or ten rams, respectively. Selection in the nucleus was simulated for five years. Selection within breed for animals which would become parents of the following generation was done across age, with selection at one year. Pathways for the following breeding flocks were simulated, i. 50 ewes and 5 rams ii. 50 ewes and 10 rams iii. 100 ewes and 5 rams iv. 100 ewes and 10 rams.

Figure 7. Selection pathway for **replacement ewes and rams**



In all breeding schemes, it was assumed that ewes lambed once annually, at a rate of 1.8 lambs per ewe with a sex ratio of 50% male and 50% female. Survival was assumed to be 75% from birth to one year of age (selection) and 80% from two to six years.

Breeding schemes were evaluated based on the annual rate of genetic gain ($\Delta G/yr$) for birth weight (BW), weaning weight (WW) and average daily gain (ADG) and changes in the annual rate of inbreeding ($\Delta F/year$). The annual rate of genetic gain is predicted using the following equation:

$$\Delta G/yr = \frac{\bar{i} r_{TI} \sigma_g}{L}$$

Where:

$\bar{i}$= intensity of selection

r_{TI}= the accuracy of selection

σ_g= genetic standard deviation

L= generation interval

Intensity of selection was calculated by using the value obtained for *p* in the table of selection intensity factors, see for example in (Falconer & Mackay, 1996).

Where *p* = (number of animals selected/total number of animals available to select from)

Upon the identification of the selection intensity it was adjusted to account for small sample size (<500).

$$\bar{i}_{\text{adjusted}} = \bar{i} - \frac{0.25}{s}$$

Where

s= number of animals selected

The accuracy of selection and genetic standard deviation were derived from heritability and standard values taken from Carrillo and Segura (1993) for BW, WW and ADG for Blackbelly sheep (Table 11.)

Table 11. Accuracy of Selection (r_{TI}) and genetic standard deviation (σ_g) for birth weight (BW), weaning weight (WW) and average daily gain (ADG) of Blackbelly sheep

	r_{TI}	σ_g
BW	0.04	2.46
WW	0.11	11.9
ADG	0.17	77.3

The generation interval was adjusted to allow for different numbers of animals in each parental age group, different lambing percentages and different survival at lambing to represent the true influence of the parents, it was calculated as:

$L_{overall} = L_{male} + L_{female} / 2$

Where:

L_{male}= Generation interval of the male which was adjusted to allow for different numbers of males in each parental group and was calculated as:

$L_{male} = \frac{\Sigma wx}{\Sigma w}$

Where:

w=number of males

x= male age

L_{female}= Generation interval of the female which was adjusted to allow for different numbers of animals in each parental group and different lambing percentages at lambing to represent the true influence of the female and was calculated as:

$L_{female} = \frac{\Sigma wx}{\Sigma w}$

Where:

w= number of ewes x reproduction rate

x= age of ewes

The annual rate of inbreeding ($\Delta F/year$), was calculated as:

$$\Delta F/year = \frac{1}{8n_m L^2} + \frac{1}{8n_f L^2}$$

Where:

n_m= Number of new males selected each year

n_f= Number of new females selected each year

L^2= generation interval squared

3.2 Scenarios Investigated

3.2.1. Change in age scenario

Ram age was varied to observe the effect of age on generation interval and consequentially, the annual rate of genetic gain. Age structure for the five-ram model was 2-yr old and 3-yr old. Ram age structure for the ten-ram model was 2-yr old, 3-yr old, 4-yr old 5-yr old and 6-yr old. Ewe age was not varied, and the same age structure was used in all models. Ewe age structure for all breeding schemes was assumed to be: 29% 2-yr old, 24% 3-yr old, 20% 4-yr old, 16% 5-yr old and 11% 6-yr old.

3.2.2. Change in selection intensity scenario

Selection intensity was changed to determine its effect on annual genetic gain. Population size was changed in breeding schemes to determine its effect on selection intensity and annual rate of inbreeding. As the population size increases, the ability to reduce the proportion of animals selected which increases selection intensity will occur (Biscarini et al., 2015), as well as easier control of inbreeding (Gandini et al., 2014). Breeding schemes were simulated for a breeding nucleus that consisted of either 50 or 100 ewes, each with five or ten rams respectively. Breeding scenarios with the following numbers were simulated: i. 50 ewes and 5 rams, ii. 50 ewes and 10 rams iii. 100 ewes and 5 rams and iv. 100 ewes and 10 rams.

3.2.3. Accuracy of selection

Heritability was simulated to represent objective and visual selection. Heritability values from Carrillo and Segura (1993) for BW, WW and ADG for Blackbelly sheep were used (Table 11.) for objective selection. No heritability estimates could be found for visual selection of BW, WW and ADG. However, it is known that visual assessment of weight is less accurate (Brown et al., 2015) so to account for the reduced accuracy, heritabilities were reduced to two thirds of the values in Table 11.

3.2.4. Crossbreeding Scenarios

There is interest in crossing the Katahdin breed from the United States over the indigenous Barbados Blackbelly. When Katahdin rams are bred to tropical hair sheep ewes, lamb mortality is reduced (Macias-Cruz, 2009), litter weaning weights per lambing are increased (Macías-Cruz, 2012) and average daily gain is greater (Hinojosa-Cuellar et al., 2011a). To simulate the crossbreeding scenarios, a nucleus flock with 50 Blackbelly ewes and five Katahdin rams was assumed. The Katahdin males were imported from the United States. A purebred Blackbelly flock was formed and maintained by importing purebred Blackbelly ewes and rams from the Ministry of Agriculture breeding flock in Barbados in 2015.

Numerous ram types can be produced from this two-breed crossing. However, simulation was limited to three options, a first cross F1 (1/2 Katahdin 1/2 Blackbelly), an upgrade (15/16 Katahdin 1/16 Blackbelly) and a composite (5/8 Katahdin 3/8 Blackbelly). In the simulations to produce each type of crossbred ram, the number of ewes (pure and crosses), number of rams (pure and crosses), number of generations and number of crosses involved were considered, as well as the number of crossbred ram lambs first produced. It was assumed that the number of lambs weaned per ewe at 1 year was 1.5, at 2 years 1.7 and 3 to 6 years 1.8. Assumptions for survival to weaning at 1 year was 85%, at 1 to 2 years 90% and 2 to 6 years 95%.

In the production of the crossbred males, two models were considered. One in which it was assumed all purebred replacement Blackbelly females would be bought from outside flocks and the other which would produce replacement Blackbelly females on farm from the existing breeding flock. This self-replacing model required the flock to be split into two breeding groups. Ewe replacement rate was assumed to be 20% annually for the purebred flock, therefore, 13 purebred Blackbelly females would be bred to purebred Blackbelly males to produce the replacements which would maintain the purebred flock. The annual rate of inbreeding ($\Delta F/year$) was calculated for the pure breeding replacement flock (13 ewes and one ram) utilizing the annual rate of inbreeding formula stated in section 1. to determine if the self-replacing option was viable. The age structure for the 50 ewe and five ram breeding schemes was used to calculate generation interval used in the $\Delta F/year$ calculation.

3.2.4.1 First Cross/F1

The aim of this approach was to create a ram with equal proportions of genes from the Katahdin and the Barbados Blackbelly (Table 12). In a model where all replacement females will be bought from outside flocks, Katahdin rams were crossed with all the Barbados Blackbelly ewes. The flock was separated into breeding groups of ten ewes and one ram. The ram offspring from this crossing would be the required genetic composition 1/2 Katahdin and 1/2 Blackbelly and would be made available to commercial farmers.

In the self-replacing model, 37 Barbados Blackbelly ewes were crossed with Katahdin rams. The flock would be split into three breeding groups of 12-13 ewes, each with one Katahdin ram. The ram offspring from this crossing would be the required genetic composition 1/2 Katahdin and 1/2 Blackbelly and would be made available to commercial farmers.

3.2.4.2 Upgrade

The aim of this breeding strategy was to observe the effects of producing a ram that has been graded up to 15/16 Katahdin (Table 12). In a model in which no purebred Blackbelly ewes are maintained, the upgraded rams were produced by crossing the Katahdin rams over all Blackbelly ewes and their crossbred offspring for three generations. The first-cross involved crossing Katahdin rams over the Blackbelly ewes. Ewes were grouped in mating pens of ten ewes with one ram. The ewes from this crossing, 1/2 Katahdin and 1/2 Blackbelly, were then crossed back to Katahdin rams. The mating groups were four groups of nine to ten ewes to one ram. Ewes from the second cross, 3/4 Katahdin and 1/4 Blackbelly, were then crossed again with Katahdin rams and split into 3 breeding groups at a ratio of eight ewes to one ram.

Table 12. Ram types and methods of production

Ram Type	Breeding Composition	Breeding Systems	Crosses & Generations	Crosses
1	1/2 K 1/2BB	Two breed fixed cross	1 generation 1 cross	K x BB
2	15/16K 1/16BB	Two breed upgrade	4 generations 4 crosses	K x BB K x 1/2k 1/2BB K x 3/4K 1/4BB K x 7/8K 1/8BB
3	5/8K 3/8 BB	Two breed composite	3 generation 4 crosses	K x BB K x 1/2K 1/2BB 3/4K 1/4BB x 1/2 K 1/2 BB

K=Katahdin, BB= Barbados Blackbelly

The resulting third cross ewes, 7/8 Katahdin 1/8 Blackbelly, became the parent ewes for the required upgraded rams. These ewes were crossed to Katahdin rams. And split into two breeding groups of eight ewes to one ram and produced the ram which was 15/16 Katahdin and 1/16 Blackbelly, which would be made available to commercial farmers.

In the self-replacing model, the upgraded rams were produced by crossing the Katahdin rams over 37 Blackbelly ewes and their crossbred offspring for three generations. In the first cross the Blackbelly ewes were grouped in mating pens of 12 -13 ewes with one Katahdin ram each. The ewes from this crossing, 1/2 Katahdin and 1/2 Blackbelly, were then crossed back to Katahdin rams. The mating groups were three groups of nine to ten ewes to one Katahdin ram. Ewes from the second cross, 3/4 Katahdin and 1/4 Blackbelly, were then crossed again with Katahdin rams and split into two groups of nine ewes. The resulting third-cross ewes, 7/8 Katahdin 1/8 Blackbelly, became the parent ewes for the required upgraded rams. These ewes were crossed to a Katahdin ram in one breeding group of 12 ewes and produced the rams which were 15/16 Katahdin and 1/16 Blackbelly, which would be made available to commercial farmers.

Throughout the duration of the breeding program mature ewes (>2 years) were managed together but separated into breeding groups at mating season. Two- and one-year olds were also managed separately and split into breeding groups at mating season.

3.2.4.3. Composite

For this breeding strategy, the aim was to observe the impact of the introduction of a crossbred sire into the breeding scheme. The composite rams were developed by mating crossbred rams to crossbred ewes. The genetic composition of the composite rams produced was 5/8 Katahdin and 3/8 Blackbelly (Table 12). The parents of the composite rams were bred from the nucleus flock of Katahdin and Barbados Blackbelly breeds.

In a model where all pure breed Blackbelly replacement females will be bought from outside flocks, the Katahdin rams were crossed over all the Blackbelly ewes. Ewes were grouped in mating pens of ten ewes with one ram. The following breeding season, the F_1 ewes from this mating were back crossed with Katahdin rams to produce the parent male, 3/4 Katahdin and 1/4 Blackbelly. The mating groups were nine to ten ewes to one male. Production of the parent female began in the second year of the breeding program. Katahdin rams were crossed over the Blackbelly ewes in mating groups of 10 ewes with one ram, producing the 1/2 Katahdin and 1/2 Blackbelly parent females. The third year of the breeding program, the crossbred parents, 3/4 Katahdin and 1/4 Blackbelly rams and 1/2 Katahdin and 1/2 Blackbelly ewes were crossed to produce the composite ram. The mating groups were eight to ten ewes to one ram. During the second year of the breeding program, the Blackbelly and F_1 ewes were managed separately. At the onset of the mating season ewes from both groups were separated into smaller breeding groups. Throughout the third year of the breeding program the two-year old and one-year old F_1 ewes were managed separately. In the self-replacing model, 37 Blackbelly females were used in the production of the composite male. The same breeding plan was followed as that of the 50 ewes with no replacement plan.

4.0 Results

4.1 Generation Interval (L)

The effect of the changes in the breeding schemes on L are shown in Table 13. When rams were used in the same proportion regardless of ewe flock size, 50 or 100, the L's are the same. Breeding schemes with ram age structure of three 2-yr old rams and two 3-yr old rams had lower ram and overall L compared to the ram breeding schemes with ram age structure of three 2-yr old, two 3-yr old, two 4-yr old, two 5-yr old and one 6-yr old rams. The L of the ewes were the same for all breeding schemes because age structure did not vary. Ewe age structure was 29% 2-yr old, 24% 3-yr old, 20% 4-yr old, 16% 5-yr old and 11% 6-yr old.

Table 13. The effect of the changes in the breeding schemes on generation interval (L) when five ram total consists of three 2-yr old and two 3-yr old and ten rams total consists of three 2-yr old, two 3-yr old, two 4-yr old, two 5-yr old and one 6-yr old, and age structure for ewe remaining at 29% 2-yr, 24% 3-yr old, 20% 4-yr old, 16% 5-yr old and 11% 6-yr old

Breeding Scheme		Generation Interval (L)		
Ewe Total	Ram Total	Ewe	Ram	Overall
50	5	3.56	2.4	2.98
50	10	3.56	3.6	3.58
100	5	3.56	2.4	2.98
100	10	3.56	3.6	3.58

4.2 Selection Intensity ($\bar{i}$)

The effect of the changes in the breeding schemes on $\bar{i}$ are displayed in Table 14. Breeding schemes with 100 ewes had greater ewe, ram and overall $\bar{i}$ than 50 ewes breeding schemes. Regardless of whether five or ten rams were used, $\bar{i}$ overall was the same for 50 ewes or 100 ewes breeding schemes

Table 14. The effect of the changes in the breeding schemes on the Selection Intensity ($\bar{i}$)

Breeding Scheme		Selection Intensity ($\bar{i}$)		
Ewe Total	Ram Total	Ewe	Ram	Overall
50	5	0.8635	1.7236	1.2936
50	10	0.8635	1.7236	1.2936
100	5	0.8717	2.0246	1.4482
100	10	0.8717	2.0246	1.4482

4.3 Accuracy of selection (r_{TI})

The effect of objective or visual selection on heritability for the traits being measured are displayed in Table 15, along with the corresponding r_{TI}. Heritability for all traits are greater when selection is done objectively compared to visually.

Table 15. The effect of objective or visual selection on heritability and accuracy of selection (r_{TI}) for birth weight (BW), weaning weight (WW) and average daily gain (ADG)

Trait	Selection method	Heritability (h^2)	r_{TI}
BW (kg)	objective	0.16	0.40
	visual	0.1056	0.32
WW (kg)	objective	0.132	0.36
	visual	0.08712	0.30
ADG (g)	objective	0.11	0.33
	visual	0.0726	0.27

4.4 Birth weight (BW)

Annual rate of genetic gain (ΔG) for birth weight when changes in generation interval (L), selection intensity ($\bar{i}$) and accuracy of selection (r_{TI}) occurs are represented in Table 16.

Table 16. Annual rate of genetic gain (ΔG) for birth weight (kg) with overall generation interval utilizing rams with 2-yr old and 3-yr old old structure (L_5) and rams with age structure of 2-yr old, 3-yr old, 4-yr old 5-yr old and 6-yr old (L_{10}), accuracy of selection done objectively (r_{TIO}) and visually (r_{TIV}) and overall selection intensity using 50 ewes ($\bar{i}_{50}$) and 100 ewes ($\bar{i}_{100}$).

	L_5		L_{10}	
	r_{TIO}	r_{TIV}	r_{TIO}	r_{TIV}
	ΔG	ΔG	ΔG	ΔG
$\bar{i}_{50}$	0.1707	0.1127	0.1421	0.0938
$\bar{i}_{100}$	0.1911	0.1261	0.1591	0.1050

Breeding schemes with generation interval L_5 had greater ΔG than breeding schemes with the generation interval L_{10}. ΔG was greater in breeding schemes with an overall selection intensity of $\bar{i}_{100}$ compared to those at $\bar{i}_{50}$. Breeding scheme L_5, $\bar{i}_{100}$, r_{TIO} had the greatest ΔG. The lowest was in the scheme L_{10}, $\bar{i}_{50}$, r_{TIV}.

4.5 Weaning weight (WW)

Annual rate of genetic gain (ΔG) for weaning weight when changes in generation interval (L), selection intensity ($\bar{i}$) and accuracy of selection (r_{TI}) occurs are represented in Table 17.

Table 17. Annual rate of genetic gain (ΔG) for weaning weight (kg) with overall generation interval utilizing rams with 2-yr old and 3-yr old old structure (L_5) and rams with age structure of 2-yr old, 3-yr old, 4-yr old 5-yr old and 6-yr old (L_{10}), accuracy of selection done objectively (r_{TIO}) and visually (r_{TIV}) and overall selection intensity using 50 ewes ($\bar{i}_{50}$) and 100 ewes ($\bar{i}_{100}$).

	L_5		L_{10}	
	r_{TIO}	r_{TIV}	r_{TIO}	r_{TIV}
	ΔG	ΔG	ΔG	ΔG
$\bar{i}_{50}$	0.6815	0.4498	0.5673	0.3744
$\bar{i}_{100}$	0.7629	0.5035	0.6350	0.4191

Breeding schemes with generation interval L_5 had greater ΔG than breeding schemes with the generation interval L_{10}. ΔG was greater in breeding schemes with an overall selection intensity of $\bar{i}_{100}$ compared to those at $\bar{i}_{50}$. Breeding scheme L_5, $\bar{i}_{100}$, r_{TIO} had the greatest ΔG. The lowest was in the scheme L_{10}, $\bar{i}_{50}$, $r_{TIV.}$

4.6 Average daily gain (ADG)

Annual rate of genetic gain (ΔG) for average daily gain when changes in generation interval (L), selection intensity ($\bar{i}$) and accuracy of selection (r_{TI}) occurs are represented in Table 18.

Table 18. Annual rate of genetic gain (ΔG) for average daily gain (g/day) with overall generation interval utilizing rams with 2-yr old and 3-yr old old structure (L_5) and rams with age structure of 2-yr old, 3-yr old, 4-yr old 5-yr old and 6-yr old (L_{10}), accuracy of selection done objectively (r_{TIO}) and visually (r_{TIV}) and overall selection intensity using 50 ewes ($\bar{i}_{50}$) and 100 ewes ($\bar{i}_{100}$).

	L_5		L_{10}	
	r_{TIO}	r_{TIV}	r_{TIO}	r_{TIV}
	ΔG	ΔG	ΔG	ΔG
$\bar{i}_{50}$	3.6892	2.4349	3.0712	2.0269
$\bar{i}_{100}$	4.1301	2.7259	3.4376	2.2688

Breeding schemes with generation interval L_5 had greater ΔG than breeding schemes with the generation interval L_{10}. ΔG was greater in breeding schemes with an overall selection intensity of $\bar{i}_{100}$ compared to those at $\bar{i}_{50}$. Breeding scheme L_5, $\bar{i}_{100}$, r_{TIO} had the greatest ΔG. The lowest was in the scheme L_{10}, $\bar{i}_{50}$, $r_{TIV.}$

4.7 Inbreeding coefficient

The effect of number of animals selected and generation interval on the rate of inbreeding is displayed in Table 19. Rates of inbreeding were observed to be greatest in breeding schemes with 5 rams. The greatest overall rate was the 50 ewe five ram breeding scheme. The lowest rate of inbreeding was in the 100 ewe 10 ram breeding scheme. The 50 ewe ten ram breeding scheme was greater than the 100 ewe ten ram breeding scheme, but still lower than the 50 ewes five ram or 100 ewe five rams breeding scheme.

Table .19 Effect of number of rams (♂) and ewes (♀) selected and generation interval (L) on annual rate of inbreeding

Breeding Scheme		New Animals		Generation Interval (L)		Rate of inbreeding (ΔF)/year
Ewe Total	Ram Total	♀	♂	L♀	L♂	(%)
50	5	15	3	3.56	2.4	0.79
50	10	15	3	3.56	3.6	0.39
100	5	30	3	3.56	2.4	0.76
100	10	30	3	3.56	3.6	0.35

4.8 Crossbreeding Scenarios

The F1 male, required the least amount of generations to be produced, the upgraded male, 15/16K 1/16BB, on the other hand, required the most (Table 20). The composite male was in between the other two breeds in both generations and crosses required for production.

Two models were considered when producing the crossbreed males. The first model assumed that all purebred replacement Blackbelly females would be bought from outside flocks. As such, all 50 Blackbelly ewes would be used in the breeding program to produce the required crossbreed males. The other model represents a self-replacing flock, where the flock would

Table 20. Ram types and methods of production

Ram Type	Breeding Composition	Breeding Systems	Generations & Crosses	Crosses
1	1/2 K 1/2BB	Two breed fixed cross	1 generation 1 cross	K x BB
2	15/16K 1/16BB	Two breed back cross	4 generations 4 crosses	K x BB K x (1/2k 1/2BB) K x (3/4K 1/4BB) K x (7/8K 1/8BB)
3	5/8K 3/8 BB	Two breed composite	3 generations 3 crosses	k x BB K x (1/2K 1/2BB) (3/4K1/4BB) x (1/2K1/2BB)

K= Katahdin BB=Barbados Blackbelly

be split into two, hence, 37 Blackbelly ewes would be used in producing the crossbreed males, and 13 Blackbelly ewes would produce purebred replacements. Table 21 displays the age structure of the self-replacing flock from which the generation interval for the ewe and ram will be determined (Table 22).

Table 21. Age structure and total animals in the self-replacing flock

	Ewe and Ram Replacement (age in years)					Total
	2	3	4	5	6	
Blackbelly ewes	4	3	3	2	1	13
Blackbelly rams	1	1				2

Table 22. Generation Interval (L) of ewes and rams in the self-replacing flock

	Generation Interval (L)
Ewe	3.47
Ram	2.5

The annual rate of inbreeding ($\Delta F/year$) for the for the self-replacing flock was calculated. This was done to determine the effect of the decreased flock size to allow for breeding of crossbreeds. The effect of number of animals selected and generation interval on the $\Delta F/year$ is displayed in Table 23.

Table 23. Effect of number of rams (♂) and ewes (♀) selected and generation interval (L) on annual rate of inbreeding of self-replacing purebred Blackbelly flock.

Breeding Scheme		New Animals		Generation Interval (L)		Rate of inbreeding (ΔF) (%)
Ewe Total	Ram Total	♀	♂	L♀	L♂	
13	2	12	2	3.47	2.5	1.09

The Central Livestock Farm (CLF) has the capacity to house 75 ewes. The population of the simulated nucleus flock is 50 ewes and five rams. Therefore, if both pure and crossbreed ewes and rams are to be maintained in the production of the required crossbreed ram, space restrictions dependent on the crossbreed ram type being produced would arise. Table 24 displays the number of crossbred ewes and rams that would be needed to produce the required crossbreed ram when all 50 ewes are bred or when flock size is reduced to accommodate self-replacement.

Table 24. Total number of crossbreed ewes and rams required to produce the required crossbred ram when breeding model assumes all purebred ewes are used, or flock size is reduced due to self-replacement

Crossbreed ram type	Breeding Model	Crossbreed ewes	Crossbreed rams	Total crossbreeds
F_1 (1/2K 1/2BB)	NR[1]	0	0	0
	R[2]	0	0	0
Upgrade (15/16K 1/16BB)	NR[1]	70	0	70
	R[2]	52	0	52
Composite (5/8K 3/8BB)	NR[1]	73	4	77
	R[2]	54	3	57

[1] all 50 ewes are bred, [2] flock size reduced to 37 ewes to accommodate self-replacement

No crossbred ewes or rams were required in the production of the F_1 ram. Production of the upgraded ram required no crossbred rams but required crossbred ewes. However, production of the composite ram required both crossbred rams and ewes. Total number of crossbred animals required were greater when the breeding schemes made no accommodation for self-replacement for both upgraded and composite rams (Table 24).

Time taken in years, number, age and genetic make-up of crossbred ewes and rams required annually in the production pathway and the number of the required crossbred ram types that could be first produced are displayed in Tables 25, 26 and 27, when the nucleus flock is 50 ewes or 37 when accommodations was made for self-replacement.

Table 26. Comparison of production pathway of upgraded (15/16K 1/16BB) and composite (5/8K 3/8BB) rams displaying time taken to produce them, the number, age and genetic makeup of ewes and rams utilised and the sex, breed and number of offspring produced in each generation assuming that all purebred Blackbelly ewes are used in crossbreed ram production and none for replacements. Composite breed production is completed in 2024

Year	Ram Type	Ewe			Ram			Offspring		
		Age years	Breed	Total	Age years	Breed	Total	Sex	Breed	Total
2020	upgrade	M	BB	50	M	K	5	♀	1/2K 1/2BB	45
	composite	M	BB	50	M	K	5	♀	1/2K 1/2BB	45
2021	upgrade	M	BB	50	M	K	5	♀	1/2K 1/2BB	45
	composite	M	BB	50	M	K	5	♀	1/2K 1/2BB	45
2022	upgrade	2	1/2K 1/2BB	34	M	K	4	♀	3/4K 1/4BB	29
	composite	M	BB	50	M	K	5	♀	1/2K 1/2BB	45
		2	1/2K 1/2BB	34			4	♂	3/4K 1/4BB	29
2023	upgrade	3	1/2K 1/2BB	33	M	K	4	♀	3/4K 1/4BB	29
		2	1/2K 1/2BB	34			4		3/4K 1/4BB	29
	composite	M	BB	50	M	K	5	♀	1/2K 1/2BB	45
		3	1/2K 1/2BB	33			4	♂	3/4K 1/4BB	29
		2	1/2K 1/2BB	34			4		3/4K 1/4BB	29
2024	upgrade	4	1/2K 1/2BB	31	M	K	4	♀	3/4K 1/4BB	28
		3	1/2K 1/2BB	33			4		3/4K 1/4BB	29
		2	3/4K 1/4BB	22			4		7/8K 1/8BB	19
	composite	4	1/2K 1/2BB	31	2	3/4K 1/4BB	4	♂	5/8K 3/8BB	28
		3	1/2K 1/2BB	33			4		5/8K 3/8BB	29
		2	1/2K 1/2BB	34			4		5/8K 3/8BB	29
2005	upgrade	5	1/2K 1/2BB	30	M	K	5	♀	3/4K 1/4BB	27
		4	1/2K 1/2BB	31					3/4K 1/4BB	28
		3	3/4K 1/4BB	21					7/8K 1/8BB	19
		2	3/4K 1/4BB	45					7/8K 1/8BB	38
2006	upgrade	6	1/2K 1/2BB	28	M	K	5	♀	3/4K 1/4BB	25
		5	1/2K 1/2BB	30					3/4K 1/4BB	27
		4	3/4K 1/4BB	20					7/8K 1/8BB	18
		3	3/4K 1/4BB	43					7/8K 1/8BB	38
		2	3/4K 1/4BB	44					7/8K 1/8BB	37
		2	7/8K 1/8BB	15				♂	15/16K 1/16BB	12

M=Mixed age, BB=Barbados Blackbelly, K=Katahdin, ♂ = only ram lambs selected, ♀ = only ewe lambs selected

Table 27. Comparison of production pathway in a self replacement model of pure Barbados Blackbelly (BB) ewes and rams and upgraded (15/16K 1/16BB) and composite rams displaying years taken to produce, the number, age and the genetic make up of the rams utilised and the sex, breed and number of offspring produced in each generation. Composite breed production is completed in 2024

Year	Ram Type	Ewe			Ram			Offspring		
		Age years	Breed	Total	Age years	Breed	Total	Sex	Breed	Total
2020	upgrade	M	BB	37	M	K	5	♀	1/2K 1/2BB	33
	composite	M	BB	37	M	K	5	♀	1/2K 1/2BB	33
	replacement	M	BB	13	M	BB	2	♀♂	BB	24
2021	upgrade	M	BB	37	M	K	5	♀	1/2K 1/2BB	33
	composite	M	BB	37	M	K	5	♀	1/2K 1/2BB	33
	replacement	M	BB	13	M	BB	2	♀♂	BB	24
2022	upgrade	2	1/2K 1/2BB	25	M	K	4	♀	3/4K 1/4BB	22
	composite	M	BB	37	M	K	5	♀	1/2K 1/2BB	33
		2	1/2K 1/2BB	25			4	♂	3/4K 1/4BB	22
	replacement	M	BB	13	M	BB	2	♀♂	BB	24
2023	upgrade	3	1/2K 1/2BB	24	M	K	4	♀	3/4K 1/4BB	29
		2	1/2K 1/2BB	25			4		3/4K 1/4BB	29
	composite	M	BB	37	M	K	5	♀	1/2K 1/2BB	33
		3	1/2K 1/2BB	24			4	♂	3/4K 1/4BB	22
		2	1/2K 1/2BB	25			4		3/4K 1/4BB	22
	replacement	M	BB	13	M	BB	2	♀♂	BB	24
2024	upgrade	4	1/2K 1/2BB	23	M	K	4	♀	3/4K 1/4BB	21
		3	1/2K 1/2BB	24			4		3/4K 1/4BB	22
		2	3/4K 1/4BB	17			4		7/8K 1/8BB	14
	composite	4	1/2K 1/2BB	23	2	3/4K 1/4BB	4	♂	5/8K 3/8BB	21
		3	1/2K 1/2BB	24			4		5/8K 3/8BB	22
		2	1/2K 1/2BB	25			4		5/8K 3/8BB	22
	replacement	M	BB	13	M	BB	2	♀♂	BB	24
2005	upgrade	5	1/2K 1/2BB	22	M	K	5	♀	3/4K 1/4BB	20
		4	1/2K 1/2BB	23					3/4K 1/4BB	21
		3	3/4K 1/4BB	16					7/8K 1/8BB	14
		2	3/4K 1/4BB	33					7/8K 1/8BB	28
	replacement	M	BB	13	M	BB	2	♀♂	BB	24
2006	upgrade	6	1/2K 1/2BB	21	M	K	5	♀	3/4K 1/4BB	19
		5	1/2K 1/2BB	22					3/4K 1/4BB	20
		4	3/4K 1/4BB	15					7/8K 1/8BB	13
		3	3/4K 1/4BB	32					7/8K 1/8BB	28
		2	3/4K 1/4BB	19					7/8K 1/8BB	16
		2	7/8K 1/8BB	11				♂	15/16K 1/16BB	9
	replacement	M	BB	13	M	BB	2	♀♂	BB	24

M=Mixed age, BB=Barbados Blackbelly, K=Katahdin, ♂ = only ram lambs selected, ♀ = only ewe lambs selected

Table 27. Generations needed to produce required crossbreed rams, to include beginning and completion of production cycle to produce the ram in years and the total number of rams that can be produced when all ewes are bred, or flock size is reduced to accommodate self-replacement

Ram type	Generations to Produce Ram	Time in years to produce ram		Rams Produced	
		Year begun	Year completed	NR[1]	R[2]
F_1 (1/2K 1/2BB)	1	2020	2020	45	33
Upgrade (15/16K 1/16BB)	4	2020	2026	12	9
Composite (5/8K 3/8BB)	3	2020	2024	58	43

[1]all 50 ewes are bred, [2] flock size reduced to 37 ewes to accommodate self-replacement

The upgrade male required the most generations to be produced, however the least number of rams were available. The greatest number of crossbred rams available was in the production of the composite ram. There were more F_1 rams available than upgraded rams but less than the composite rams Table 27.

The upgraded male required three different crossbreed ewes to be produced, compared to one to produce the composite male, Tables 25 and 26.

5.0 Discussion

This study was carried out to determine appropriate systems to improve the sheep breeding program at the government operated Central Livestock Farm (CLF). To achieve this, three aspects were addressed, firstly methods to increase the rate of annual genetic gain, secondly to consider the annual rate of inbreeding within the indigenous Barbados Blackbelly breed and finally to investigate production of crossbreed rams from exotic and indigenous breeds . The crossbreed rams were of particular interest as there exists a growing interest by farmers in the introduction of exotic breeds into their flocks in order to improve production, particularly carcass size. As a result, farmers look to the CLF as a facility that could provide crossbreed rams to meet their needs.

This study initially focused on the evaluation of pure breeding schemes for a nucleus flock of varying population sizes. Pure breed simulations were developed using the Barbados Blackbelly, (de Almeida, 2018),an indigenous breed of the Latin America and Caribbean region (LAC). The mating strategy to produce crossbreed rams also involved the Barbados Blackbelly as well as the Katahdin (Rasali et al., 2006) a composite breed developed in the United States used widely throughout the LAC. The effect on a nucleus herd when producing crossbreed rams of different genetic makeup was considered.

This chapter will discuss the ability of the government operated nucleus flock, of small size (50 – 100 ewes), to address breed improvement of the indigenous Barbados Blackbelly. Pure breeding schemes were simulated for a nucleus that consisted of either 50 or 100 ewes, each with five or ten rams respectively. These breeding schemes were evaluated based on annual rate of genetic gain for birth weight (BW), weaning weight (WW) and average daily gain (ADG) for different scenarios: age, selection intensity and accuracy of selection. Due to small individual flock size in developing countries, genetic improvement within flock is limited, therefore the concept of central nucleus flocks are often implemented as a means of assisting genetic improvement (Gizaw et al., 2011).

Objective selection had higher heritabilities than subjective selection. In the absence of heritabilities for visually assessed BW, WW and ADG, it was assumed that the heritabilities estimated for objective data were reduced by one third to arrive at the heritabilities for subjectively assessed weight traits. Unsurprisingly, the rates of genetic gain were higher for objectively measured BW, WW and ADG and this superiority can be used to justify the cost of purchasing weighing equipment. Gizaw et al. (2014a) also noted that visually assessed weight traits had reduced rates of genetic gain in all village breeding schemes.

Generation interval was calculated with variations only in the age structure of the rams in the different breeding schemes, ewe age structure remained unchanged. In this study, the breeding schemes with

2-yr old and 3-yr old rams had the lowest generation interval. As expected, the results confirmed that a short generation interval had a positive effect on annual genetic gain (Buch et al., 2012). Breeding schemes with only 2-yr old and 3-yr old rams displayed greater annual genetic gain in BW, WW and ADG in contrast to schemes with 2-yr, 3-yr, 4-yr, 5-yr and 6-yr old rams.

This study highlighted the importance of the age of the breeding ram in determining the annual rate of genetic gain of the weight traits. Therefore, the Government of Dominica through the CLF could introduce genomic selection to obtain increased gains. Genomic selection allows for better characterization of the breeding rams compared to selected rams (Ducrocq et al., 2018), as well as accelerated gains even when progeny testing is disregarded (Buch, 2010; Shumbusho, 2013), because the time period associated with progeny testing increase the generation interval (Rupp et al., 2016). By introducing genomic selection, the interaction between accuracy of selection and generation interval will be lessened (Buch, 2010). The introduction of genomic systems may be limited by the cost (Rupp et al., 2016) as well the availability of competent human resources (Ducrocq et al., 2018). However, consideration could be made to carry out genotyping of only the breeding rams, to reduce cost considering their importance in the breeding programs as suggested by Shumbusho (2013).

Breeding schemes with 100 ewes displayed greater overall selection intensity than 50 ewe breeding schemes. However, it was not the ewe population size that was the determining factor, since the selection intensity for 50 and 100 ewe breeding schemes were similar, 0.8635 and 0.8717 respectively. This is because the proportion of ewes selected did not change based on population size. The proportion of replacements selected at one year of age in the nucleus flock showed that greater emphasis was placed on the rams (three rams and 15 ewes out of 90 lambs of both sexes for the 50 ewe breeding schemes and three rams and 30 ewes out of 180 lambs of both sexes for the 100 ewe breeding scheme). The combination of a decreased proportion of sires selected and an increase in male to female ratio in the 100 ewe breeding schemes in contrast to the 50 ewe breeding schemes, resulted in increased selection intensity in rams, thereby positively affecting the overall selection intensity and increasing the annual rate of genetic gain in the weight traits measured. This was in agreement with results for Egyptian buffalo (Abdel-Salam et al., 2006; Abdel-Salam et al., 2010) which demonstrated an increase in selection intensity in bulls resulted in greater annual genetic gain in overall milk production. The CLF should focus its breeding strategies on increasing selection intensity in its breeding rams, rather than having larger breeding populations. Besides, the information from the study indicates that an increase in the overall selection intensity of the rams positively influences the annual rate of genetic gain, it also means that the CLF is able to incur savings by maintaining less animals but not jeopardizing the quality of animals being made available to farmers.

The nucleus which would be most fitting for the CLF would be the 50 ewe five ram breeding scheme. Although this breeding scheme displayed the highest annual rate of inbreeding amongst the four schemes, it was still well below the 1% recommended rate by the FAO (1998) and the population is within the carrying capacity (75 ewes) of the sheep unit at the CLF. The 50 ewe, ten ram, breeding scheme had a much lower annual rate of inbreeding, second only to the 100 ewe ten, ram breeding scheme. However, annual rates of genetic gain for the three weight traits were all lower than that of the 50 ewe, five ram, breeding scheme. The 100 ewe five ram, breeding scheme had a slightly lower annual rate of inbreeding than the 50 ewe, five ram, breeding scheme and the highest overall rates of annual genetic gain for the three traits amongst the four breeding schemes. However, the flock size is greater than the carrying capacity of the present sheep unit at the CLF and unless decisions are made to increase the flock size, housing and pastures, this breeding scheme will not be feasible.

The estimated rate of inbreeding for all breeding schemes was less than the 1% and target flock sizes were equal to and greater than the 50, recommended by the FAO (1998). Smaller effective population sizes increases the rate of inbreeding(Falconer & Mackay, 1996), as the choice of mates becomes limited, leading to mating of close relatives. Declining flock size was attributed as a factor in increasing rates of inbreeding by Muasya et al. (2014) when studying dual purpose goats. However, in this study, it was also observed that an increase rate of inbreeding occurred when breeding ram numbers and generation interval were reduced, indicating an association between inbreeding and breeding population structure. Reduction in sire population was attributed to an increase in the inbreeding coefficient of Guilan (Eteqadi et al., 2014) and Baluchi (Gholizadeh & Ghafouri-Kesbi, 2016) sheep in Iran. This is supported by the FAO (1998) who stated that a longer generation interval will result in a lower rate of inbreeding. The carrying capacity of the ewe unit at the CLF is well over the minimum (50 ewes) indicated by FAO (1998), as such an effective flock size can be maintained without the fear of undesirable inbreeding rates. The breeding schemes with the highest rates of inbreeding also possessed the highest rates of annual genetic gain for the weight traits and were well within the acceptable rates of inbreeding. Flock size of the Barbados Blackbelly at the CLF should always be maintained above 50 and the number of new rams introduced into the breeding flock should be monitored so that it does not allow the rate of inbreeding to go beyond 1% because of their impact on generation interval.

It is not recommended that cross breeding at the CLF should incorporate self-replacement of pure-breed animals as a component of the breeding program with the model examined in this study. Due to the small number of animals that would be allocated to the self-replacement flock in order to satisfy the 20% replacement rate, the annual rate of inbreeding would be above the recommended 1%. Additionally, a flock designated for self-replacement, from the total breeding flock, reduces the number of crossbreed males that can be produced. In order to consider self-replacement, additional investments to increase flock size, housing and pasture would be required. Whereas, the current flock size can be maintained, and all breeding ewes can be allocated to producing crossbreed rams with pure-breed replacements being purchased annually.

Of the three cross-breed rams, the recommendations would be to produce the composite ram at the CLF. This study focused on the period and crosses needed to produce crossbreed rams. Beyond this period, and not captured in this study, but detailed in many others, is that once formed, composite breeding systems produce animals of a stable breed composition, which means new animals need not be purchased (Shrestha & Fahmy, 2007). This means that unlike the upgrade which would require the continuous maintenance of pure-breed stock and three different cross-breed ewe flocks, and the F_1 which would require the continuous maintenance of a pure breed and one cross-breed ewe flock, for production, only one flock of composite ewes would be required for production of composite rams.

Considerably more time and animals would be needed to produce the upgraded ram compared to the composite. In the 6th year of the breeding program when the upgrade would be produced, only 15 ewes with the required genetic make-up would be available for producing only 12 upgraded rams. On the other hand, in the 4th year of the breeding program 98 ewes of the required gene combination would be available to annually produce 86 composite rams.

At present, the CLF is not able to effectively support conservation of the indigenous Barbados Blackbelly and simultaneously produce crossbreed rams for farmers because of a limitation of flock size and land allocated for sheep production. To achieve both, its recommended that resources are made available to increase infrastructure that can support a 50 ewe five ram Barbados Blackbelly flock and another flock of the same size of composite animals possibly of the 5/8 Katahdin and 3/8 Barbados Blackbelly mix as demonstrated in this study.

5.1 Limitations

A limitation to this study was the assumption that pure breed Barbados Blackbelly ewes gave birth to only one litter annually when carrying out the analysis for genetic gain for the three weight traits. Barbados Blackbelly sheep are known to have a high reproductive performance with lambing intervals under nine months (Knights et al., 2012)however, the possibility of multiple litters annually and its effects on genetic gain was not considered.

This study only considered the time needed to produce the first set of required crossbreed rams which would be made available to farmers, and not the overall time required to entirely replace all the breeding ewes in the flock with the desired crossbreeds, which is also another limitation. Inclusion of this would have displayed the overall time and number of crossbreeds required in the entire replacement process and not simply the time and number of animals obtained at the production of the first required crossbreed rams. The analysis was limited to only three crossbreed types and utilization of only two breeds. The inclusion of other crossbreed types and increasing the number of breeds into the breeding program would have allowed for a wider analysis because of the influence of total number of breeding animals that would be needed, as well as time.

5.2 Implications

The results of this study support the findings that a reduction in the generation interval will lead to an increase in annual genetic gain. Generation interval in the breeding rams had a greater effect on genetic gain compared to the ewes in this study. Therefore, steps to further reduce the generation interval at the Central Livestock Farm during the breeding process should be made a primary focus in increasing genetic gain particularly in the breeding rams.

The present study indicates that when producing the crossbreed rams, the total time for replacement of the breeding flock from pure breed Barbados Blackbelly ewes to the required crossbreed ewes differs between upgrades and composites. The fact that all ewes were replaced by the fourth year of the breeding program in the production of the composite ram was a good result, particularly because no pure breeds will be needed to produce replacements. On the other hand, only 30% of replacement females was produced at the sixth year of the breeding program to produce the upgrade ram. Displaying the entire period to produce all replacements in the upgrade breeding program would highlight the difference in the total number of animals needed and how that would translate into management of scare resources to support this breeding program. This study suggests that the Central Livestock Farm can produce more crossbreed ram lambs in a shorter time by producing a composite animal.

5.3 Future Research

This research can used as a starting point for future studies on government owned and managed livestock breeding stations throughout the Latin America and Caribbean region. This study considered annual genetic gain in weight traits, however analysis of traits of importance such as maternal and parasitic resistance will allow for comparisons with these findings. This study was of a closed nucleus breeding scheme, however, further studies which would consider an open nucleus breeding can be considered to compare results of the present findings. Additionally, future research will allow scientists to determine which breeds and crossbreeds are the most appropriate to be utilized in the Latin America and Caribbean region. Finally, other research which includes new technologies such as artificial insemination, embryo transfer and genomics can be carried out to determine the impact genetic gain and compare with present findings.

6.0 Conclusion

The results of the present study indicated that annual rate of genetic gain for BW, WW and ADG when changes are made in generation interval, selection intensity and accuracy of selection was always greater when accuracy of selection was done objectively compared to subjectively. Overall, the 100 ewe, five rams breeding flock when analysed objectively had the greatest annual rate of genetic gain. The population of replacements selected at one year of age in the nucleus showed that greater emphasis was placed on rams, suggesting that the combination of a decreased proportion of sires selected and an increase in male to female ratio resulted in the increase in genetic gain. However, the most appropriate flock size for the CLF is the 50 ewe, five rams breeding scheme, which had the second highest rates of genetic gain, because of space limitations at the Central Livestock Farm.

Inbreeding coefficient was greater in breeding schemes with five rams; however, these rates were still acceptable because they were at the recommended rate of < 1%. It is also important to note that when simulations were done in 50 ewe, five rams flocks meant to produce crossbreed rams and are self-replacing, the rate of inbreeding was > 1%. This suggests that the Central Livestock Farm may not possess the capacity to carry out the breeding of crossbreed rams and self-replacement of pure breeds simultaneously. Additionally, it was found that the production of crossbreed composite rams was quicker in both periods to produce the first ram as well as to replace all ewes to crossbreed ewes from purebred. Additionally, the production of crossbreed composite rams produced the most rams during the period of study. The added benefit of this scheme is that another pure breed flock is not needed to produce replacements, as these can now come from within, translating into less mature animals kept at the Central Livestock Farm and resources can be directed to solely one flock of breeding animals.

This study gave an insight into the management decisions that needs to be taken on small sized government owned and operated livestock breeding stations not only in The Commonwealth of Dominica, but throughout the Latin America and Caribbean region. It highlights how easily genetic resources can be lost due to indiscriminate breeding and the management and financial and human resources needed to effectively operate such an institution. Continuous studies are required to determine efficiency of production of indigenous breeds as well controlled crossbreeding schemes.

7.0 References

Abdalla, E. B., Kotby, E. A., & Johnson, H. D. (1993). Physiological responses to heat-induced hyperthermia of pregnant and lactating ewes *SmallRuminant Research, 11*, 125-134

Abdel-Moneim, A. Y., Ahmed, A. M., Ibrahim, M. M., & Mokhtar, M. M. (2009). Flock dynamics of desert Barki sheep in relation to age structure. *Tropical Animal Health Production, 41*(6), 899-905. doi:10.1007/s11250-008-9277-4

Abdel-Salam, S. A., Nigm, A. A., Elsayed, M., Sadek, R. R., & Abdel-Aziz, A. S. (2006). *Genetic gain of milk production in Egyptian buffalo as affected by population size, nucleus size and selection intensity in open nucleus breeding scheme* Paper presented at the 35th ICAR Session and INTERBULL Meeting. , Kuopio, Finland.

Abdel-Salam, S. A., Sayed, A. I., Elsayed, M., & Abou-Bakr, S. (2010). Genetic gain in open nucleus breeding scheme to improve milk production in Egyptian Buffalo. *Livestock Science, 131*(2-3), 162-167. doi:10.1016/j.livsci.2010.03.013

Abraham, H., Gizaw, S., & Urge, M. (2019). Simulated alternative breeding schemes for optimizing Begait goat improvement programs in Western Tigray, northern Ethiopia. *Agricultural Systems, 176*. doi:10.1016/j.agsy.2019.102669

Annett, R. W., Carson, A. F., Dawson, L. E., Irwin, D., & Kilpatrick, D. J. (2011). Effects of breed and age on the performance of crossbred hill ewes sourced from Scottish Blackface dams. *Animal, 5*(3), 356-366. doi:10.1017/S1751731110002090

Archimède, H., Pellonde, P., Despois, P., Etienne, T., & Alexandre, G. (2008). Growth performances and carcass traits of Ovin Martinik lambs fed various ratios of tropical forage to concentrate under intensive conditions. *Small Ruminant Research, 75*(2-3), 162-170. doi:10.1016/j.smallrumres.2007.10.001

Arroyo, L. J., Gallegos-Sanchez, J., Villa-Godoy, A., Berruecos, J. M., Perera, G., & Valencia, J. (2007). Reproductive activity of Pelibuey and Suffolk ewes at 19 degrees north latitude. *Animal Reproduction Science, 102*(1-2), 24-30. doi:10.1016/j.anireprosci.2006.09.025

Avril, D., Lallo, C. H. O., Percy, K., Bourne, G., Thomas, P., & Warner, R. (2011). Pre-wean performance of lambs from Barbados Black belly and West African type ewes reared under a pasture based system in the humid tropical environment of Tobago, West Indies. *Tropical Agriculture (Trinidad), 88*, 6.

Ayichew, D. (2019). Dorper sheep cross breeding with Indigenous sheep breed in Ethiopia. *Journal of Applied and Advanced Research, 4*(1). doi:10.21839/jaar.2019.v4i1.250

Barillet, F., Marie, C., Jacquin, M., Lagriffoul, G., & Astruc, J. M. (2001). The French Lacaune dairy sheep breed: use in France and abroad in the last 40 years. *Livestock Production Science, 71*(1), 17-29. doi:10.1016/s0301-6226(01)00237-8

Biscarini, F., Nicolazzi, E. L., Stella, A., Boettcher, P. J., & Gandini, G. (2015). Challenges and opportunities in genetic improvement of local livestock breeds. *Frontiers in Genetics, 6*, 1-7. doi:10.3389/fgene.2015.00033

Bishop, S. C. (2012). Possibilities to breed for resistance to nematode parasite infections in small ruminants in tropical production systems. *Animal, 6*(5), 741-747. doi:10.1017/S1751731111000681

Blasco, M., Campo, M. M., Balado, J., & Sanudo, C. (2019). Effect of Texel crossbreeding on productive traits, carcass and meat quality of Segurena lambs. *Journal of Science Food and Agriculture, 99*(7), 3335-3342. doi:10.1002/jsfa.9549

Bosso, N. A. (2006). *Genetic improvement of livestock in tsetse infested areas in West Africa.* (PhD Doctoral). Wageningen U iversity, Wageningen, The Netherlands. (90-8504-333-6)

Bowdridge, S., MacKinnon, K., McCann, J. C., Zajac, A. M., & Notter, D. R. (2013). Hair-type sheep generate an accelerated and longer-lived humoral immune response to Haemonchus contortus infection. *Veterinary Parasitology, 196*(1-2), 172-178. doi:10.1016/j.vetpar.2013.01.008

Bradford, G. E., Fitzhugh, H. A., & Dowding, A. (1983). Reproduction and birth weight of Barbados Blackbelly sheep in the Golden Grove flock, Barbados. In H. A. Fitzhugh & G. E. Bradford (Eds.), *Hair sheep of Western Africa and the Americas, a genetic resource for the Tropics.* (pp. 163-170): Westview Press.

Brown, D. J., Savage, D. B., Hinch, G. N., & Hatcher, S. (2015). Monitoring liveweight in sheep is a valuable management strategy: a review of available technologies. *Animal Production Science, 55*(4), 427-436. doi:10.1071/an13274

Buch, L. H., Sorensen, M. K., Berg, P., Pedersen, L. D., & Sorensen, A. C. (2012). Genomic selection strategies in dairy cattle: Strong positive interaction between use of genotypic information and intensive use of young bulls on genetic gain. *Journal of Animal Breeding and Genetics, 129*(2), 138-151. doi:10.1111/j.1439-0388.2011.00947.x

Buch, L. H., Sørensen, M.K., Lassen, J. P. Berg,P., Sørensen, A.C. (2010). *Dairy cattle breeding schemes with or without geneomic selection or progeny testing.* Paper presented at the Proceedings of the 9th World Congress on Genetics Applied to Liveststock Production Leipzig, Germany.

Buckley, F., Lopez-Villalobos, N., & Heins, B. J. (2014). Crossbreeding: implications for dairy cow fertility and survival. *Animal, 8* 122-133. doi:10.1017/S1751731114000901

Burgos-Gonzalez, C., Huerta-Aparicio, M., Aguirre, V., Vazquez, R., Orihuela, A., & Pedernera, M. (2018). Short communication: milk production and lamb development in Saint Croix and Katahdin hair sheep breeds (Ovis aries). *Tropical Animal Health and Production, 50*(3), 683-687. doi:10.1007/s11250-017-1448-8

Burke, J. M., Apple, J. K., Roberts, W. J., Boger, C. B., & Kegley, E. B. (2003). Effect of breed-type on performance and carcass traits of intensively managed hair sheep. *Meat Science, 63*, 309-315.

Burke, J. M., & Miller, J. E. (2004). Relative resistance to gastrointestinal nematode parasites in Dorper, Katahdin, and St. Croix lambs under conditions encountered in the southeastern region of the United States. *Small Ruminant Research, 54*(1-2), 43-51. doi:10.1016/j.smallrumres.2003.10.009

Carneiro, H., Louvandini, H., Paiva, S. R., Macedo, F., Mernies, B., & McManus, C. (2010). Morphological characterization of sheep breeds in Brazil, Uruguay and Colombia. *Small Ruminant Research, 94*(1-3), 58-65. doi:10.1016/j.smallrumres.2010.07.001

Carrillo, L., & Segura, J. C. (1993). Environmental and genetic effects on preweaning growth performance of hair sheep in Mexico. *Tropical Animal Health and Production, 25*(3), 173-178. doi:10.1007/bf02236237

Cassell, B., & McAllister, J. (2009). Dairy Crossbreeding Research Results from Current Projects. *Virginia Cooperative Extension, 404-094*, 1-6.

Chay-Canul, A. J., Aguilar-Urquizo, E., Parra-Bracamonte, G. M., Piñeiro-Vazquez, Á. T., Sanginés-García, J. R., Magaña-Monforte, J. G., . . . López-Villalobos, N. (2019). Ewe and lamb pre-weaning performance of Pelibuey and Katahdin hair sheep breeds under humid tropical conditions. *Italian Journal of Animal Science, 18*(1), 850-857. doi:10.1080/1828051x.2019.1599305

Cloete, S. (2012). Breeding in Developing Countries and Tropics. *Encylopedia of Sustainablity, Science and Technology, 19*(12), 1-55.

de Almeida, A. M. (2018). Barbados Blackbelly: the Caribbean ovine genetic resource. *Tropical Animal Health and Production, 50*(2), 239-250. doi:10.1007/s11250-017-1475-5

de Waal, H. O., & Combrinck, W. J. (2000). The development of the Dorper, its nutrition and a perspective of the grazing ruminant on veld. *Small Ruminant Research, 36*(2), 103-117. doi:10.1016/s0921-4488(99)00155-8

Dickerson, G. E. (1973). Inbreeding and Heterosis inAnimals. *Journal of Animal Science, 1973*, 54-77.

Dubey, A., Jain, A., Gadpaylae, R., Bara, D. K., Yadav, A., Vikas Kumar, V., & Sahu, J. (2019). Importance and utilization of non-additive genetic variance in farm animals. *Journal of Entomology and Zoology Studies, 7*, 1561-1564.

Ducrocq, V., Laloe, D., Swaminathan, M., Rognon, X., Tixier-Boichard, M., & Zerjal, T. (2018). Genomics for Ruminants in Developing Countries: From Principles to Practice. *Frontier in Genetics, 9*, 1-7. doi:10.3389/fgene.2018.00251

Eteqadi, B., Ghavi Hossein-Zadeh, N., & Shadparvar, A. A. (2014). Population structure and inbreeding effects on body weight traits of Guilan sheep in Iran. *Small Ruminant Research, 119*(1-3), 45-51. doi:10.1016/j.smallrumres.2014.03.003

Falconer, D. S., & Mackay, T. F. C. (1996). *Introduction to quantitative genetics* (4th ed.). Burnt Mill, England: Longman.

FAO. (1998). *Secondary Guidelines for Development of National Farm Animal Genetic Resources Management Plan*. Retrieved from Rome, Italy:

FAO. (2014). *FAO Statistical Yearbook 2014 Latin America and the Caribbean food and agriculture*.

FAO. (2015). *The second report on the state of the world's animal genetic resource for food and agriculture*. Retrieved from Rome:

FAO. (2016). *Marketing and production models for small ruminant products in the Caribbean region*. Retrieved from

Fogarty, N. M. (2006). *Utilization of breed resources for sheep production*. Paper presented at the Proceedngs of the 8th World Congress on Genetics Applied to Livestock Production, Minas Gerais, Brazil. http://www.wcgalp8.org.br/

Galina, M. A., Morales, R., Silva, E., & Lopez, B. (1996). Reproductive performance of Pelibuey and Blackbelly sheep under tropical management systems in Mexico. *Small Ruminant Research, 22*, 31-37.

Gandini, G., Del Corvo, M., Biscarini, F., & Stella, A. (2014). Genetic improvement of small ruminant local breeds with nucleus and inbreeding control: A simulation study. *Small Ruminant Research, 120*(2-3), 196-203. doi:10.1016/j.smallrumres.2014.06.004

Garcia, M., Chapman, C. K., & Despain, D. (2019). Applying Principles of Crossbreeding to Maximize Hybrid Vigor In (pp. 5): Utah State University.

Gatenby, R. M., Doloksaribu, M., Bradford, G. E., Romjali, E., Batubara, A., & Mirza, I. (1996). Comparison of Sumatra sheep and three hair sheep crossbreds II. Reproductive performance of F1 ewes. *Small Ruminant Research, 25*, 161-167.

Getachew, T., Haile, A., Wurzinger, M., Rischkowsky, B., Gizaw, S., Abebe, A., & Solkner, J. (2016). Review of sheep crossbreeding based on exotic sires and among indigenous breeds in the tropics: An Ethiopian perspective. *African Journal of Agricultural Research, 11*(11), 901-911. doi:10.5897/ajar2013.10626

Gholizadeh, M., & Ghafouri-Kesbi, F. (2016). Inbreeding depression in growth traits of Baluchi sheep. *Small Ruminant Research, 144*, 184-190. doi:10.1016/j.smallrumres.2016.09.012

Gicheha, M. G., Kosgey, I. S., Bebe, B. O., & Kahi, A. K. (2006). Evaluation of the efficiency of alternative two-tier nucleus breeding systems designed to improve meat sheep in Kenya. *Journal of Animal Breeding and Genetics, 123*(4), 247-257. doi:10.1111/j.1439-0388.2006.00598.x

Gizaw, S., Getachew, T., Goshme, S., Valle-Zarate, A., van Arendonk, J. A., Kemp, S., . . . Dessie, T. (2014a). Efficiency of selection for body weight in a cooperative village breeding program of Menz sheep under smallholder farming system. *Animal, 8*(8), 1249-1254. doi:10.1017/S1751731113002024

Gizaw, S., Getachew, T., Tibbo, M., Haile, A., & Dessie, T. (2011). Congruence between selection on breeding values and farmers’ selection criteria in sheep breeding under conventional nucleus breeding schemes. *Animal, 5*(7), 995-1001. doi:10.1017/s1751731111000024

Gizaw, S., Komen, H., & van Arendonk, J. A. M. (2009). Optimal village breeding schemes under smallholder sheep farming systems. *Livestock Science, 124*(1-3), 82-88. doi:10.1016/j.livsci.2009.01.001

Gizaw, S., Lemma, S., Getachew, T., Abebe, A., Goshme, S., & Tegegne, A. (2014b). Designing crossbreeding programs for small holder sheep farms in Ethiopia. *Ethiopian Journal of Animal Production, 14*, 1-15.

Gizaw, S., Rischkowsky, B., Valle-Zarate, A., Haile, A., van Arendonk, J. A., Mwai, A. O., & Dessie, T. (2014c). Breeding programs for smallholder sheep farming systems: I. Evaluation of alternative designs of breeding schemes. *Journal of Animal Breeding and Genetics, 131*(5), 341-349. doi:10.1111/jbg.12101

Gizaw, S., van Arendonk, J. A., Valle-Zarate, A., Haile, A., Rischkowsky, B., Dessie, T., & Mwai, A. O. (2014d). Breeding programmes for smallholder sheep farming systems: II. Optimization of cooperative village breeding schemes. *Journal of Animal Breeding and Genetics, 131*(5), 350-357. doi:10.1111/jbg.12102

Godfrey, R. W., Gray, M. L., & Collins, J. R. (1997). Lamb growth and milk production of hair and wool sheep in a semi-arid tropical environment. *Small Ruminant Research, 24*, 77-83.

González-Domínguez, G., Hinojosa Cuéllar, J. A., Oliva-Hernández, J., Torres Hernandez, G., Candelario, J., Segura-Correa, J. C., . . . El Carmen García-Osorio, I. (2016). Preweaning growth analysis of Blackbelly lambs in hot humid weather. *Nova Scientia, 17*, 181-197.

González Garduño, R., Torres Hernández, G., & Castillo Álvarez, M. (2002). Growth of Blackbelly lambs between birth and final weight in the humid tropics of Mexico. *Veteranario Mexico, 33*, 443-453.

Graham, B. (2012). *Profile of the Small Scale Farming in the Caribbean*.

Haenlein, G. F. W. (2007). About the evolution of goat and sheep milk production. *Small Ruminant Research, 68*(1-2), 3-6. doi:10.1016/j.smallrumres.2006.09.021

Haile, A., Wurzinger, M., Mueller, J., Mirkena, T., Duguma, G., Rekik, M., . . . Rischkowsky, B. (2020). *Guidelines for setting up commuity based small ruminants breeding program.* Beirut, Lebanon 1108-2010.: ICARDA.

Hinojosa-Cuellar, J. A., Torres-Hernandez, G., Oliva-Hernandez, J., Aranda-Ibanez, E., Segura-Correa, J. C., & and Gonzalez -Camacho, J. M. (2011a). Preweaning performance of lambs from purebred and crossbred hair ewes under humid tropical conditions of Tabasaco Mexico. *Journal of Animal and Veterinary Advances, 10*, 3149-3154.

Hinojosa-Cuellar, J. A., Torres-Hernandez, G., Oliva-Hernandez, J., Aranda-Ibanez, E., Segura-Correa, J. C., & Gonzalez-Camacho, J. M. (2011b). Pre-Weaning Performance of Lambs from Purebred and Crossbred Hair Ewes under Humid Tropical Conditions of Tabasco, Mexico. *Journal of Animal and Veterinary Advances, 10*(23), 3149-3154. Retrieved from <Go to ISI>://WOS:000298097200021

Kaeppler, S. (2012). Heterosis: Many Genes, Many Mechanisms—End the Search for an Undiscovered Unifying Theory. *ISRN Botany, 2012*, 1-12. doi:10.5402/2012/682824

Knights, M., Siew, N., Ramgattie, R., Singh-Knights, D., & Bourne, G. (2012). Effect of time of weaning on the reproductive performance of Barbados Blackbelly ewes and lamb growth reared in the tropics. *Small Ruminant Research, 103*(2-3), 205-210. doi:10.1016/j.smallrumres.2011.09.042

Kosgey, I. S., Baker, R. L., Udo, H. M. J., & Van Arendonk, J. A. M. (2006). Successes and failures of small ruminant breeding programmes in the tropics: a review. *Small Ruminant Research, 61*(1), 13-28. doi:10.1016/j.smallrumres.2005.01.003

Kosgey, I. S., & Okeyo, A. M. (2007). Genetic improvement of small ruminants in low-input, smallholder production systems: Technical and infrastructural issues. *Small Ruminant Research, 70*(1), 76-88. doi:10.1016/j.smallrumres.2007.01.007

Kridli, R. T., Abdullah, A. Y., Mohamed Momani, Shaker, M. M., & Al-Momani, A. Q. (2016). Age at Puberty and Some Biological Parameters of Awassi and its First Crosses with Charollais and Romanov Rams. *Italian Journal of Animal Science, 5*(2), 193-202. doi:10.4081/ijas.2006.193

Kridli, R. T., Abdullah, A. Y., Shaker, M. M., & Masa'deh, M. K. (2010). Sexual activity and puberty in pure Awassi and crosses and backcrosses with Charollais and Romanov sheep breeds. *New Zealand Journal of Agricultural Research, 50*(4), 429-436. doi:10.1080/00288230709510310

Kumar, M., Ratwan, P., & Kumar, A. (2016). Heterosis–Genetic Basis and Utilization for Improvement of Dairy Cattle: A Review *Journal of Dairy Science andTechnology, 5*, 40-50.

Leroy, G., Baumung, R., Boettcher, P., Scherf, B., & Hoffmann, I. (2016). Review: Sustainability of crossbreeding in developing countries; definitely not like crossing a meadow. *Animal, 10*(2), 262-273. doi:10.1017/S175173111500213X

Leymaster, K. A. (1987). The crossbred sire :Experimental results for sheep. *Journal of Animal Science, 65*, 110-116.

Leymaster, K. A. (2002). Fundamental Aspects of Crossbreeding of Sheep: Use of breed diversity to improve the effeciency of meat production. *Sheep and Goat Research Journal, 17*, 50-59.

Macías-Cruz, U. A.-V., F.D. ; Olguín-Arredondo, H.A. ; Molina-Ramirez, L. ; Avendano-Reyes,L. (2012). Pelibuey sheep synchronized with progestogen and mated to males Katahdin and Dorper breeds under stabled conditions: production of sheep and lamb growth during the pre-weaning. *Archivos de Medicina Veterinaria, 44*, 29-37.

Macias-Cruz, U. Á.-V., F.D.; Correa-Calderón ,A,; MolinaRamírez ,L.; González-Reyna , A.; Soto-Navarro,S & Avendaño-Reyes,L. (2009). Pelibuey Ewe Productivity and Subsequent Pre weaning Lamb Performance Using Hair sheep Breeds Under a Confinement System. *Journal of Applied Animal Research, 36*, 255-260. doi:10.1080/09712119.2009.9707071

Mbuku, S. M., Okeyo, A. M., Kosgey, I. S., & Kahi, A. K. (2015). Optimum crossbreeding systems for goats in low-input livestock production system in Kenya. *Small Ruminant Research, 123*(1), 55-61. doi:10.1016/j.smallrumres.2014.10.001

McManus, C., Paiva, S. R., & Olegário de Araújo, R. (2010). Genetics and breeding of sheep in Brazil. *Sociedade Brasileira de Zootecnia, 39*, 236-246.

Milne, C. (2000). The history of the Dorper sheep. *Small Ruminant Research, 36*(2), 99-102. doi:10.1016/s0921-4488(99)00154-6

Mishra, S. P., Taraphder, S., Roy, M., Sarkar, U., Datta, S., Saikhom, R., . . . Mohanty, D. (2017). Breeding techniques to exploit non-additive gene action for improvement of livestock. *Bulletin of Environment, Pharmacology and Life Sciences, 6*, 126-134.

Mortimer, S. I., van der Werf, J. H. J., Jacob, R. H., Pethick, D. W., Pearce, K. L., Warner, R. D., . . . Hopkins, D. L. (2010). Preliminary estimates of genetic parameters for carcass and meat quality traits in Australian sheep. *Animal Production Science, 50*, 1135-1144.

Muasya, T. K., Githinji, M. G., Mugambi, J. N., & Ilatsia, E. D. (2014). Effect of inbreeding on growth performance of dual purpose gaots in semi-arid kenya. *Research Gate*, 1-5.

Mueller, J. P., Rischkowsky, B., Haile, A., Philipsson, J., Mwai, O., Besbes, B., . . . Wurzinger, M. (2015). Community-based livestock breeding programmes: essentials and examples. *Journal of Animal Breeding and Genetics, 132*(2), 155-168. doi:10.1111/jbg.12136

Muñoz-Osorio, G. A., Aguilar-Caballero, A. J., Sarmiento-Franco, L. A., Wurzinger, M., & Alavez-Ramírez, A. (2018). Post-weaning growth of pure and crossbred hair lambs under the tropical Mexican conditions. *Archivos de Zootecnia, 67*, 5. doi:10.21071/az.v67i257.3399

Munoz-Osorio, G. A., Aguilar-Caballero, A. J., Sarmiento-Franco, L. A., Wurzinger, M., & Camara-Sarmiento, R. (2016). Technologies and Strategies for Improving Hair Lamb Fattening Systems in Tropical Regions: A Review. *Ecosistemas Y Recursos Agropecuarios, 3*(8), 267-277. Retrieved from <Go to ISI>://WOS:000411090800014

Nasrat, M. M., Segura Correa, J. C., & Magaña Monforte, J. G. (2016). Breed genotype effect on ewe traits during the pre-weaning period in hair sheep under the tropical Mexican conditions. *Small Ruminant Research, 137*, 157-161. doi:10.1016/j.smallrumres.2016.03.026

Notter, D. R. (1987). The crossbred sire: theory. *Journal of Animal Science, 65*(1), 99-109. doi:10.2527/jas1987.65199x

Notter, D. R. (2012). Genetic improvement of reproductive efficiency of sheep and goats. *Animal Reproduction Science, 130*(3-4), 147-151. doi:10.1016/j.anireprosci.2012.01.008

Notter, D. R., Mousel, M. R., Lewis, G. S., Leymaster, K. A., & Taylor, J. B. (2017). Evaluation of Rambouillet, Polypay, and Romanov-White Dorper x Rambouillet ewes mated to terminal sires in an extensive rangeland production system: Lamb production. *Journal of Animal Science, 95*(9), 3851-3862. doi:10.2527/jas2017.1619

Nurse, G., Cumberbatch, N., & McKenzie, P. (1983). Performance of Barbados Blackbekky sheep and their crosses at the Ebini station, Guyana. In H. A. Fitzhugh & G. E. Bradford (Eds.), *Hair sheep of Western Africa and the Americas, a genetic resource for the Tropics* (pp. 119-123): Westview Press.

Oishi, A., Kahi, A. K., Nagura, Y., Fujita, M., & Hirooka, H. (2008). Effect of culling age of does on milk and meat production in Japanese-Saanen goats

Livestock Science, 114, 13. doi:10.1016/j.livsci.2007.05.003

Ortega-Jimenez, E., Alexandre, G., Boval, M., Archimède, H., Mahieu, M., & Xandé, A. (2005). Intake and milk production of suckling ewes reared at pasture in humid tropics according to the post-grazing residue management. *Animal Research, 54*(6), 459-469. doi:10.1051/animres:2005039

Paim, T. P., Bianchini, E., Esteves, G., Daltro, D. S., Cardoso, C. C., Braccini Neto, J., & McManus, C. (2019). Meat production performance from crossbreeding between locally-adapted hair sheep and specialized breeds. *Archivos de Zootecnia, 68*, 46-52.

Park, Y. W., & Haenlein, G. F. W. (Eds.). (2006). *Handbook of milk of non-bovine mammals* (1st ed.). 2121 State Avenue, Ames, Iowa 50014, USA: Blackwell Publishing Professional.

Petrović, M. P., Sretenović, L., Muslić, D. R., Pacinovski, N., & Maksimović, N. (2009). The effect of crossbreeding systems on lamb meat production. *Macedonian Journal of Animal Science, 1*, 57-60.

Price, E. O., Estep, D. Q., Wallach, S. J. R., & Dally, M. R. (1991). Sexual Performance of Rams as Determined by Maturation and Sexual Experience. *Journal of Animal Science, 69*(3), 1047-1052. Retrieved from <Go to ISI>://WOS:A1991FW97900021

Pryce, J. E., Goddard, M. E., Raadsma, H. W., & Hayes, B. J. (2010). Deterministic models of breeding scheme designs that incorporate genomic selection. *Journal of Dairy Science, 93*(11), 5455-5466. doi:10.3168/jds.2010-3256

Ptáček, M., Ducháček, J., Stádník, L., & Fantová, M. (2017). Effects of age and nutritional status at mating on the reproductive and productive traits in Suffolk sheep kept under permanent outdoor management system. *Czech Journal of Animal Science, 62*(No. 5), 211-218. doi:10.17221/63/2016-cjas

Rasali, D. R., Shrestha, J. N. B., & Crow, G. H. (2006). Development of composite sheep breeds in the world: A review. *Canadian Journal of Animal Science, 86*(1), 1-24. Retrieved from <Go to ISI>://WOS:000240050200001

Rastogi, R. K. (2001). Production performance of Barbados blackbelly sheep in Tobago, West Indies. *Small Ruminant Research, 41*(2), 171-175. doi:10.1016/s0921-4488(01)00199-7

Rios-Utrera, A. C.-R., R. ; Lagunes-lagunes, J. ; Oliva-Hernández, J. (2014). Preweaning weight gain in Pelibuey lambs and their crosses with blackbelly dorper and katahdin. *Nova Scientia, 12*, 273-286.

Romero-Escobedo, E., Torres-Hernández, G., Becerril-Pérez, C. M., Alarcón-Zúñiga, B., Apodaca-Sarabia, C. A., & Díaz-Rivera, P. (2016). A comparison of Criollo and Suffolk ewes for resistance to Haemonchus contortus during the periparturient period. *Journal of Applied Animal Research, 46*(1), 17-23. doi:10.1080/09712119.2016.1252378

Rupp, R., Mucha, S., Larroque, H., McEwan, J., & Conington, J. (2016). Genomic application in sheep and goat breeding. *Animal Frontiers, 6*(1), 39-44. doi:10.2527/af.2016-0006

Sanchez-Davila, F., Bernal-Barragan, H., Padilla-Rivas, G., Del Bosque-Gonzalez, A. S., Vazquez-Armijo, J. F., & Ledezma-Torres, R. A. (2015). Environmental factors and ram influence litter size, birth, and weaning weight in Saint Croix hair sheep under semi-arid conditions in Mexico. *Tropical Animal Health and Production, 47*(5), 825-831. doi:10.1007/s11250-015-0795-6

Segura, J. C., Sarmiento, L., & Rojas, O. (1996). Productivity of Pelibuey and Blackbelly ewes in Mexico under extensive management. *Small Ruminant Research, 21* 6.

Shrestha, J. N. B. (2005). Conserving domestic animal diversity among composite populations. *Small Ruminant Research, 56*(1-3), 3-20. doi:10.1016/j.smallrumres.2004.06.014

Shrestha, J. N. B., & Fahmy, M. H. (2007). Breeding goats for meat production 2. Crossbreeding and formation of composite population. *Small Ruminant Research, 67*(2-3), 93-112. doi:10.1016/j.smallrumres.2005.10.018

Shumbusho, F., Raoul, J., Astruc,J.M., I. Palhiere, I. and ElsenJ.M. (2013). Potential benefits of genomic selection on genetic gain of small ruminant breeding programs. *Journal of Animal Science, 91:*, 3644–3657. doi:10.2527/jas2012-6205

Solomon, J., Cumberbatch, N., Austin, R., Gonsalves, J., & Seaforth, E. (2006). The production parameters of the Barbados Blackbelly and crossbred sheep in a controlled semi-intensive system. *Livestock Research for Rural Development., 18*, 11. Retrieved from http://www.lrrd.org/lrrd18/4/solo18055.htm

Sousa, W. N., Ojeda, M. D. B., Faco, O., & Cartaxo, F. Q. (2011). Genetic improvement of goats in Brazil: Experiences, challenges and needs. *Small Ruminant Research, 98*(1-3), 147-156. doi:10.1016/j.smallrumres.2011.03.032

Souza, L. D., Carneiro, P. L. S., Malhado, C. H. M., Silva, F. F. E., & da Silveira, F. G. (2013). Traditional and alternative nonlinear models for estimating the growth of Morada Nova sheep. *Revista Brasileira De Zootecnia-Brazilian Journal of Animal Science, 42*(9), 651-655. Retrieved from <Go to ISI>://WOS:000322905400007

Spangler, M. L. (2007). *The value of heterosis in cow herds: Lessons from the past that apply to today*. Paper presented at the The Range Beef Cow Symposium XX Fort Collins, Colorado.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B, 365*(1554), 2853-2867. doi:10.1098/rstb.2010.0134

Tibbo, M., Philipsson, J., & Ayala, W. (2006). *Sustainable Sheep Breeding Programmes in the Tropics a framework for Ethiopia*. Paper presented at the Conference on International Agricultural Research for Development

University of Bonn, Germany.

van der Werf, J. H. J., Kinghorn, B. P., & Banks, R. G. (2010). Design and role of an information nucleus in sheep breeding programs. *Animal Production Science, 50*(11-12), 998-1003. doi:10.1071/An10151

Vargas Junior, F. M., Martins, C. F., Pinto Gdos, S., Ferreira, M. B., Ricardo Hde, A., Leao, A. G., . . . Teixeira, A. (2014). The effect of sex and genotype on growth performance, feed efficiency, and carcass traits of local sheep group Pantaneiro and Texel or Santa Ines crossbred finished on feedlot. *Tropical Animal Health and Production, 46*(5), 869-875. doi:10.1007/s11250-014-0579-4

Wakchaure, R., Ganguly, S., Praveen, P. K., Sharma, S., Kumar, A., Mahajan, T., & Qadri, K. (2015). Importance of Heterosis in Animals : A Review *International Journal of Advanced Engineering Technology and Innovative Science (IJAETIS), 1*, 1-5.

Wildeus, S. (2011). *Accelerated hair sheep lamb production systems in the tropics :Joining three times in two years.* Paper presented at the 5 International Symposium on Goat and Sheep Production - 5 SINCORTE, Joao Pessoa, Paraiba, Brazil, .

Yadav, V., Singh, P. N., Sharma, R., Gupta, A., Baranwal, A., Ahmad, S. F., & Raina, V. (2018). Crossbreeding systems of livestock *The Pharma Innovation Journal, 7*, 8-13.

Yilmaz, M., Altin, T., Karaca, O., Cemal, I., Bardakcioglu, H. E., Yilmaz, O., & Taskin, T. (2011). Effect of body condition score at mating on the reproductive performance of Kivircik sheep under an extensive production system. *Tropical Animal Health and Production, 43*(8), 1555-1560. doi:10.1007/s11250-011-9841-1

Zygoyiannis, D. (2006). Sheep production in the world and in Greece. *Small Ruminant Research, 62*(1-2), 143-147. doi:10.1016/j.smallrumres.2005.07.043