Development of a U.S. fine wool selection index

by

Tamra L. Kott

B.S., Texas A&M University, 2019

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Animal Sciences & Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2022

Approved by:

Major Professor
Alison Crane

Copyright

Abstract

Genetic evaluation in the United States (U.S.) sheep industry has previously lacked emphasis on fine wool quality traits. The Western range index (WRI) was the only index provided through National Sheep Improvement Program (NSIP) to include grease fleece weight (GFW) and fiber diameter (FD). As the market shifts and the military continue to support U.S. wool, greater emphasis on the selection of fine wool quality and production is needed to meet the needs of shifting market conditions. The objectives of this thesis were to estimate economic drivers of fine wool production and provide U.S. producers with an effective fine wool selection index to evaluate the genetic performance of fine wool production. Breeding objectives were developed through evaluation of survey responses obtained from production, marketing, and processing sectors of the sheep industry. Respondents across all sectors indicated that FD, GFW, staple length (SL), staple strength (SS), character, body weight (BW), and fleece yield (YLD) should be included in a selection index. Through adjustments due to database constraints and measurement limitations, the final traits included in the breeding objective were FD, GFW, SL, fiber diameter coefficient of variation (FDCV), and curvature (CURV). Economic values were determined through communications with fine wool industry leaders and available market information (6.08 or 5.75 for GFW, -0.227 or -0.124 for FD, 0 for SL, -0.039 for FDCV, and 0.0042 for CURV) and led to the development of four potential indices. Due to severe economic nonlinearity in SL, the economic values were applied to restricted matrix calculations to produce a restricted index weight for SL. The economic values and the restricted index weight of SL were then used to evaluate each index for sensitivity to economic weights. Overall, efficiency loss was less than 1% across the four indices, indicating they were all robust to changes in economic values. The final index proposed for the NSIP database was 6.08 GFW – 0.227 FD – 0.099 SL –

0.039 FDCV + 0.0042 CURV as it was the fastest, most aggressive approach to selection for increased GFW and decreased FD. Selection utilizing this index is expected to emphasize increased GFW and decreased FD, whereas decreased FDCV and increased CURV were given minimal importance. Due to the index restriction, SL is expected to remain the same. Overall, the proposed U.S. fine wool index may be utilized to increase fine wool production and quality.

Table of Contents

List of Figures x
List of Tables xi
List of Equations xii
Abbreviations xiii
Acknowledgements xvi
Chapter 1 - Literature Review 1
- Introduction 1
  - Global Wool Industry 1
    - Australia 2
    - China 3
    - United States 5
- Wool Harvesting & Marketing in the United States 8
  - Wool Traits 9
    - Fiber Diameter 9
      - Fiber diameter grading systems 9
      - Fiber diameter and variation measurement 10
      - Causes of fiber diameter variability 19
      - Measurements of fiber diameter variation 20
    - Staple Length, Strength, and Variation 21
      - Staple Length 21
      - Staple Strength 23
      - Staple Length and Strength Variation 24
    - Fleece Weight 25
    - Fleece yield 26
    - Wool style 28
      - Color 29
      - Crimp 32
      - Staple density, dust penetration, and staple weathering 34
  - Wool Harvest Preparation 35

Shearing Preparation 36
Wool Clip Preparation 37
Wool Clip Testing 40
Core Testing 40
Grab Sampling 42
Wool Marketing 43
Marketing Channels 43
Producer 44
Wool Pools and Cooperatives 45
Wool Warehouses 47
Sales Methods 48
Private treaty 48
Sealed bid 48
Auction-based 49
Role of wool buyers 49
Genetic improvement of the United States fine wool industry 50
Genetic parameters of individual traits 50
Heritability 52
Genetic Correlation 55
Fiber Diameter 55
Staple Length 56
Grease Fleece Weight 58
Clean Fleece Weight 59
Yield 60
Fiber Diameter Coefficient of Variation 61
Curvature 63
Phenotypic correlation 64
Fiber Diameter 64
Staple Length 66
Grease Fleece Weight 68
Clean Fleece Weight 69

Yield 71
Fiber Diameter Coefficient of Variation 72
Curvature 73
Conclusion 74
Establishing economically relevant traits 74
Theory of establishing economic values 75
Non-Objective 76
Objective 78
Establishing economic values in the wool industry 82
Selection indices: theory, development, utilization 83
Selection index theory development 84
Selection index creation 86
Selection index utilization 89
Conclusions 92
References 94
Chapter 2 - National wool production survey of sheep industry stakeholders 124
Introduction 124
Materials & Methods 127
Survey design 127
Survey distribution 130
Survey analysis 130
Results & Discussion 132
Demographics 132
Selection criteria ranking 134
Producer responses 134
Marketing responses 136
Processor responses 138
Trait improvement opinions 140
Producer responses 140
Processing & Marketing responses 142
Trait preferences 143

High priority trait inclusion 144
Preferences of wool traits in comparison to grease fleece weight 145
Mature ewe size and relationship between frame size and wool traits 147
Conclusion 150
References 152
Chapter 3 - Fine Wool Production: Index Development 172
Introduction 172
Materials & Methods 175
General 175
Economic Values 176
Fiber Diameter 177
Staple Length 177
Grease Fleece Weight 179
Fiber Diameter Coefficient of Variation and Curvature 180
Index Analysis 181
Selection index coefficients 181
Selection index accuracy 183
Sensitivity analysis 184
Spearman rank correlations 185
Results & Discussion 185
Economic values 185
Fiber diameter and fiber diameter coefficient of variation 186
Curvature and grease fleece weight 187
Staple length 188
Index coefficients and calculations 188
Index coefficients 188
Index Accuracy 188
Sensitivity analysis 190
Spearman rank correlations 191
The proposed fine wool index 193
Conclusion 194

References... 197

List of Figures

Figure 1.1 Decline in United States wool production from 1935 to 2020 based on total kilograms produced (USDA-NASS, 2021a). 109

Figure 1.2 Decline in United States number of sheep shorn from 1935 to 2020 (USDA-NASS, 2021a). 110

Figure 1.3 2019 United States wool export destinations (USDA-ERS, 2020). 111

Figure 1.4 United States wool imports from 1990 to 2019 (USDA-ERS, 2020). 112

Figure 2.1 Number of national wool production survey respondents by years in the sheep industry 157

Figure 2.2 Map of National wool production survey respondents by state 158

Figure 2.3 Wool production respondents' opinion of staple length of the United States flock and their individual flock 165

Figure 2.4 Wool production respondents' opinion of the yearling weights of their individual flock 166

Figure 2.5 Producer and combined marketer and processor preferences of the inclusion of wool traits in a fine wool index 167

Figure 2.6 Production and combined marketing and processing respondents' wool trait preferences in comparison to grease fleece weight 168

Figure 2.7 Commercial, seedstock, and combination producer respondents' preferences of wool traits compared to grease fleece weight 169

Figure 2.8 Respondents' opinion, by category, on yield and grease fleece weight as drivers for mature animal size 170

Figure 2.9 Respondents' opinion, by category, on if the fine wool index should account for the regulation of mature animal size 171

List of Tables

Table 1.1 The American, English, and Micron grading systems (Kott, 1993). 113

Table 1.2 Heritability estimates of wool production traits 114

Table 1.3 Heritability estimates of wool quality traits.. 115

Table 1.4 Heritability estimates of body weight traits 116

Table 1.5 Genetic and Phenotypic correlations of wool and body weight traits 117

Table 2.1 All producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock.. 159

Table 2.2 Commercial producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock 160

Table 2.3 Combination producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock 161

Table 2.4 Seedstock producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock 162

Table 2.5 Marketing respondents (weighted average) rankings of various criteria for making purchasing decisions 163

Table 2.6 Processing respondents (weighted average) rankings of various criteria for making purchasing decisions 164

Table 3.1 Descriptive statistics of NSIP wool phenotypes for breeds A and B.......................... 201

Table 3.2. Economic values for index A, B, C, and D.. 202

Table 3.3. Descriptive statistics of NSIP EBV records within the top 10% of Western Range Index values (14,501 animals) 203

Table 3.4. Index coefficients for index A, B, C, and D 204

Table 3.5. Efficiency losses for index A, B, C, and D.. 205

Table 3.6. Spearman rank correlations between the Western Range Index and index A, B, C, and D.. 206

List of Equations

Equation 1.1) Aggregate genotype estimation 86
Equation 1.2) Selection index estimation 86
Equation 1.3) Maximization of the correlation between H and I 87
Equation 1.4) Index weight estimation 87
Equation 1.5) Index value estimation using estimated breeding values 88
Equation 1.6) Index value estimation using expected breeding values and index coefficients 89
Equation 1.7) Index coefficient estimation 89
Equation 3.1) Index weight estimation 181
Equation 3.2) Index coefficient estimation for a genetic index 182
Equation 3.3) Restricted index coefficient 182
Equation 3.4) Genetic index accuracy 183
Equation 3.5) Traditional index accuracy 183
Equation 3.6) Efficiency calculation 184
Equation 3.7) The fine wool selection index 193

Abbreviations

°/mm .... degrees per millimeter
AF .... Airflow meter
ASI .... American Sheep Industry
ASTM .... American Society of Testing Materials
AU .... auction-based
AWEX .... Australian Wool Exchange Limited
AWI .... Australia Wool Innovation Limited
AWTA .... Australian Wool Testing Authority
BLUP .... Best Linear Unbiased Prediction
BOU .... bellies out untied
BW .... body weight
CFW .... clean fleece weight
cm .... centimeter
CMS .... cooperative marketing system
CO-OP .... cooperative
CURV .... curvature
DP .... dust penetration
EBV .... estimated breeding value
ERT .... economically relevant trait
FD .... fiber diameter
FDA .... Fibre Distribution Analyser
FDCV .... fiber diameter coefficient of variation
FDSD .... fiber diameter standard deviation
FFDA .... Fibre Fineness Distribution Analyser
FIDAM .... Fibre Image Display and Measurement
FL .... FibreLux Micron Meter
FS .... full table skirt
FW .... fleece weight
FWC .... Fine Wool Consortium

GFW .... grease fleece weight
IWTO .... International Wool Textile Organisation
kg .... kilogram
ktex .... kilotex
LS .... SIROLAN LASERSCAN
mm .... millimeters
NIR .... Near Infrared Reflectance Spectroscopy
NSIP .... National Sheep Improvement Program
NRC .... National Research Council
OFDA .... Optical Fiber Diameter Analyser
PM .... projection microscope
PT .... private treaty
REV .... relative economic value
SAS .... Statistical Analysis Software
SB .... sealed bid
SC .... spinning count
SIFAN .... Single Fiber Analyser
SL .... staple length
SRC .... Spearman rank correlation
SS .... staple strength
STD .... staple density
TIA .... Technology Innovation Agency
U.S. .... United States
USDA .... United States Department of Agriculture
VM .... vegetable matter
WP .... wool pool
WRI .... Western range index
WW .... wool warehouse
WWT .... weaning weight
YLD .... fleece yield
YWT .... yearling weight

μm .... micrometer

USITC .... United States International Trade Commission

Acknowledgements

First and foremost, I need to thank the Fine Wool Consortium for not only providing me with a funding source, but also for the technical support and guidance through this process. Thank you for the opportunity to come to Kansas State University and work on a project that I feel will have a critical impact on the American wool industry. Also, a special thank you to Dr. Ron Lewis, Rusty Burgett, and Ben Lehfeldt for all your help with the NSIP database, your selection index knowledge, and technical expertise.

To my committee, thank you for giving me the opportunity to be pushed out of my comfort zone and learn about such a fast-growing aspect of the livestock industry. To my major professor Dr. Alison Crane, thank you for allowing me to be your first graduate student. I feel like we have both grown professionally and personally through this experience and appreciate you giving me the opportunity to be part of your program. Dr. Jennifer Bormann, thank you for being the open door that I could come to with all my thoughts on animal breeding principles. Thank you for being the voice of reason when I had overly ambitious writing and editing goals. Dr. Bob Weaber, thank you for being a wealth of knowledge, and always being someone I could call with my questions while developing this selection index.

I also need to acknowledge my fellow graduate students for the wonderful times that we had. From an impromptu sword fight to a biscuits and gravy making contest all the fun in and out of the office made the tough times worth it. To Ashley Hartman and the rest of the Hillcrest household, thank you for including me as an honorary roommate and inviting me to every BBQ and movie night. Thank you for keeping me in check and giving me support when I honestly did not think I would ever get finished. To Drew Lakamp thank you for being my office buddy and helping me with everything statistics, I honestly would not be here without you. Thank you for being keeping in touch even after you had defended and putting up with all my random texts and calls. To Will Schaefer, thank you for your help with all things coding, you saved me many hours of stress and frustration, and I still say I would still be analyzing data if it weren't for you. To all of the K-State Animal Sciences and Industry graduate students, you all have become my Kansas family and are some of the best friends I have ever had.

Finally, I need to thank my family and friends outside of K-State. To my parents and brother, thank you for your patience, support, and understanding through this process. From the late-night calls to the trips back and forth from Kansas, and even a couple back to College Station, I appreciate your unwavering support through this process and am happy to say it has all paid off. Also, a big thank you to my friends outside of K-State that supported me through late night calls, holiday reunions, and road trips. Thank you for reminding me that I have a life outside of graduate school.

Chapter 1 - Literature Review

Introduction

The United States (U.S.) fine wool industry is in a position of opportunity as wool import and export markets shift, consumer demand for sustainable products continue to increase, and wool products continue to expand into the outdoor apparel market according to the American Sheep Industry (ASI, 2021). As changes to global and domestic wool markets occur, the U.S. fine wool industry will need greater emphasis on the improvement of fine wool production and quality, because the U.S. has declined as a major competitor in the global wool market (Anderson et al., 2009). Regression of the U.S. wool industry was mainly caused by the simultaneous loss of wool volume, as domestic production has deteriorated since the 1940s. Compared to major producing countries such as Australia and New Zealand, decline in wool quality further contributed to the country's decline as a competitor in the global industry (National Research Council; NRC, 2008; Anderson et al., 2009). If the U.S. wool industry can improve both the quantity and quality of its wool clip, it may be possible to take full advantage of the changing market conditions and attain a higher production percentage of the global market share. Industry leaders can improve the U.S. wool clip by increasing producer awareness of international wool quality standards and implementation of genetic selection tools for improved wool production.

Global Wool Industry

Global fiber production has grown exponentially, doubling over the last 20 yr (Textile Exchange, 2020). However, world wool production accounted for slightly less than 1% (1.07 million t of wool being produced in 2019) of the total 111 t of world fiber production. This global share of fiber production has remained relatively stagnant at around 1% since 2008, after a steady decline due to the rise of man-made synthetic fibers in the mid to late 20th century (Erdogan et al., 2020; Textile Exchange, 2020). Synthetic fiber textiles initially rose in popularity due to cheaper manufacturing costs and the ability to make more uniform textile products (Kumar and Suganya, 2017). Nevertheless, wool's lower energy production and renewability present an opportunity for increased demand as the trend for natural and sustainable materials has risen in recent years (Erdogan et al., 2020). As consumer interest in sustainable materials continues to grow, major wool-producing countries, such as Australia and China, stand to gain the most from this environmentally friendly trend.

Australia

By country, Australia dominates global wool exports, with over 183 million kilograms (kg) of clean wool exported in 2018 (Giebel, 2020). Australia is also regarded as the top producer of fine wool, with a clean wool market share just below 25% in 2017 (Erdogan et al., 2020). Strong marketing and advertising strategies, superior sorting and handling in production, and increased trade are just a few aspects that make Australia the leading country for global wool production.

The country's aggressive wool marketing and advertising campaigns began with the rise of synthetic fiber production in the mid 1900s (Ferrero-Regis, 2020). To stay in the competition, the Australian government established the Australian Wool Board to harness resources and promote research and marketing of wool. The Australian Wool Board pushed an innovative campaign to promote wool as a high fashion fiber through magazines, fashion shows, radio programs, and other marketing avenues. Like the American Angus Association promoting Certified Angus Beef as a superior beef product, the Australian Wool Board elevated Australian Merino wool as a superior fiber, known for its unmatched comfort and quality.

Australia’s superior wool sorting and handling methods helped the country attain an exceptional level of wool quality that set the standard for fine wool in the international market. For example, the utilization of skirting and classing, or grouping fleeces, was and still is a widely used practice (Couchman, 2012). The fleece is first skirted, in which inferior wool is removed from the fleece; it is then classified based on various quality aspects of the fleece (Anderson et al., 2009). This technique produces a clean product that can be measured objectively for quality when marketed. Wool is sold at higher prices when skirted and classed, as it creates a more homogeneous product that can be processed more efficiently.

Australian wool is in great international trade demand by countries with high levels of wool processing (Ferrero-Regis, 2020). The proximity and strong trade relations with major Asian wool markets and the great distance from major lamb markets contribute to Australia's majority control of the wool industry (NRC, 2008). Furthermore, cheaper freight costs to Asian countries prompted global wool trade with Australia due to shorter transport times and easy wool storage, which positively influenced profit potential.

Based on 2019 International Wool Textile Organization (IWTO) provisional data, Australia produces more wool exports (273,559 t) than its major competitors: New Zealand, South Africa, the United Kingdom, Mongolia, and Argentina combined (201,154 t; IWTO, 2021), while the U.S. produced a mere 3,658 t. China has contributed little to the global market for wool fiber exports, yet it should not be underestimated. With almost all its production going directly to domestic processing centers, China is the second-largest wool producer in the world.

China

Even though Australia dominates in wool production, the majority of wool processing infrastructure is under Chinese control, making it the world's leading raw wool importer and manufacturer of finished wool products such as apparel (Erdogan et al., 2020). Beginning in the 1980s, wool processing capacity in China increased, resulting from low labor costs, governmental reforms that increased the ease of entry into the processing industry, and high wool production levels (Liu et al., 2011). These factors eventually made China the top wool processor in the world, as most of the world's wool processing capacity was moved from Western Europe to Asian countries, primarily China, in the 1990s.

China is second only to Australia in total raw wool production (Erdogan et al., 2020). However, it's wool production is not intended for high-end apparel, but for felt and carpet making, due to its quality and character (Longworth et al., 2010). Though fine wool demand increased, and wool production nearly doubled over the past 40 yr, China's fine wool production has stagnated from a lack of economic incentives and higher prices for lamb meat products (Liu et al., 2011).

Due to China's disequilibrium between fine wool production and demand, its processing capacity exceeds production levels, causing the country to rely on imports to keep its processing mills running efficiently and meet global demands (Liu et al., 2011). In 2009, wool imports to China accounted for 33% of total world wool outputs, satisfying over 80% of the country's total processing capacity. Furthermore, the Australia Wool Innovation Limited (AWI) reported that only 30% of the wool processed in China is exported as textiles, while approximately 70% is used domestically (AWI, 2004). Due to the demand of both domestic and international markets for diversified, high-quality products, the future of China's import market continues to look strong (Longworth et al., 2010). However, further expansion depends on several factors, such as: alternative fiber competition and availability, concerns regarding environmental protection that may limit processing levels, and continued domestic demand for fine wool products (Liu et al., 2011). Chinese demand for fine wool greatly impacts the global wool industry as China imports wool from many countries. In 2008, the major wool suppliers to China included Australia, New Zealand, Uruguay, and South Africa (Liu et al., 2011). Still, other countries, such as the U.S., also export a large percentage of their wool clip to China. Due to lack of processing mills, the U.S. relies heavily on China to import U.S. raw wool and wool textile products.

United States

When U.S. wool production peaked in the 1940s, the country was a major competitor in the global wool market, ranking 5th for wool production (NRC, 2008). Unfortunately, after this peak, U.S. wool production severely declined due to higher lamb prices, the creation of synthetic fibers, and the loss of wool processing infrastructure. As production declined, the U.S. plummeted in the global production market and has been producing less than 1% of global wool output (Anderson et al., 2009). The decrease in production can be seen in United States Department of Agriculture (USDA) records of the number of sheep shorn and kg of wool produced since 1935, as shown in Figures 1.1 and 1.2 (USDA-NASS, 2021a). For example, in 1975, 14.47 million sheep were shorn in the U.S., producing a total of 54.52 million kg of wool; however, in the past 44 yr there has been a dramatic decline with 3.32 million sheep shorn, generating 10.89 million kg of raw, greasy wool (USDA-SRS, 1976; USDA-NASS, 2021b, respectively). Though production levels have declined, wool production still represented over $40 million worth of economic benefits to the U.S. in 2019.

The primary geographic locations of production have experienced relatively little change over the years. In 2019, more than half of the wool produced in the U.S. was grown in California, Colorado, Wyoming, Utah, Texas, and South Dakota (USDA-NASS, 2021b). Apart from Utah, all these states were top wool producers in the 1970s to 90s (USDA-SRS, 1976;

USDA-NASS, 1996). One notable change was the recent decline in Texas wool production, which caused the state to lose its place as the top wool producer. The Texas decline primarily resulted from increased popularity of hair-type sheep, specifically Dorpers, which gained a foothold in the state during the mid-1990s to early 2000s (Riley et al., 2020). This breed increased in prevalence because of its hardy, productive nature, and its added benefit of not needing to be shorn. As the cost of shearing rose due to the shortage of shearing crews, the lack of available wool in hair sheep operations became an advantage for some producer's (Whitney et al., 2009). The Texas wool industry is not the only one that has dealt with tight profit margins, as commercial wool operations around the nation deal with a lack of government assistance, shearing crews, and domestic marketing opportunities in some regions. These factors, in addition to higher lamb prices and a reduced average fleece weight (FW) per head, have pushed producers to look to other means of increasing returns (USDA-SRS, 1976; USDA-NASS, 2021b). Notably, these industry challenges are primarily directed towards the commercial sector. Outside of the commercial sector, prices and profit margins can vary widely depending on the market, such as the higher prices paid for hand-spinning fleeces (the art of making yarn by hand). While most non-commercial wool product marketing occurs domestically, commercial industry trading occurs on international and domestic fronts.

In the past 15 years, more than 50% of commercially produced U.S. wool has been exported due to apparel production having moved to countries with cheaper manufacturing costs (USDA-ERS, 2020). Exports in 2019 amounted to approximately 63% of U.S. clean wool production, with the greatest portion going to China, followed by Egypt and India (Figure 1.3; USDA-ERS, 2020). Due to recent instability of the top export market, however, the American wool industry began promoting to alternative markets in India, Western Europe, Southeast Asia, and Mexico (ASI, 2021). The U.S. has focused its marketing resources on these countries to monitor the growth of new textile manufacturing operations.

While exports are sent for high-end apparel processing in other countries, remaining U.S. production levels have failed to satisfy domestic wool processing demand for carpet production and apparel production of knits and flannel (NRC, 2008). However, American wool imports began to decline rapidly in 1993 due to changing fashion trends, such as casual work dress codes that increased the use of cotton and synthetics in place of wool apparel according to United States International Trade Commission reports and USDA data (Figure 1.4; USITC, 1998; USDA-ERS, 2020). The exponential drop in wool imports did not slow until the late 2000s, where it has remained relatively stable at an average of 3.38 million kg per year (Figure 1.4; USDA-ERS, 2020). Most U.S. imports have been traditionally sourced from New Zealand and Australia. New Zealand makes up over 55% of the coarser half of wool imported into the U.S., with a majority likely going to carpet-type textile products (NRC, 2008; USDA-ERS, 2020). Conversely, Australia contributes approximately 42% of the finer half of wool imports, used for apparel products from blankets to tweed suits. In part, this import need is because a portion of domestic production goes directly into military attire through the Berry Amendment (Grasso, 2014). Enacted in 1941, just before U.S. entry into World War II, this amendment was designed to guarantee that the U.S. military was fed and clothed with American products through domestic source restrictions on products such as clothing and fabrics. These source restrictions prevent the U.S. Department of Defense from acquiring foreign clothing and fabrics not produced in the U.S. (Grasso, 2014). Even today, the Berry Amendment remains an integral part of U.S. wool demand, ensuring that the armed forces only purchase domestically produced wool. Wool remains a vital inclusion in military uniforms even with the rise in synthetic fibers. The flameresistant qualities of wool make it an ideal fiber for war zones since many synthetic fibers do not perform well in high temperatures where they may burn or even melt (ASI, 2021). Along with the U.S. military, demand for hosiery is another production avenue that holds a percentage of domestic wool consumption (ASI, 2021). The high-performance properties of wool, such as temperature regulation and odor control, make it ideal for socks. With the application of shrink treatments that make the products machine washable, wool hosiery production is on the rise.

Whether it be importing or exporting, the destination is highly dependent on the end-product desired. Various retail products such as carpet or tailor-made suits require wool with varying levels of quality attributes (Wood, 2003). For this reason, it is vital to understand the variations in wool quality before making any marketing decisions.

Wool Harvesting & Marketing in the United States

The U.S. wool industry encompasses a large variety of management practices and production systems. Wide variations in genetics, environment, and breed diversity across the wool industry influence physical characteristics of wool, leading to a heterogeneous product. Individual wool fleeces have several measurable characteristics used to group fleeces together into similar lots (Lupton, 1989; NRC, 2008). Measured by objective and subjective assessment methods, these traits are used to determine the overall quality and value of the wool. The major wool characteristics include fiber diameter (FD), grease fleece weight (GFW), clean fleece weight (CFW), fleece yield (YLD), staple length (SL), staple strength (SS), color, style, vegetable matter (VM), stain, crimp, and variability of SL and FD. When developing effective selection programs, knowledge of these wool traits and how they are associated is essential to success (Fogarty, 1995).

Wool Traits

Fiber Diameter

The primary economic determinant of wool quality is FD, as it directly correlates to processing performance (processing efficiency and yarn quality produced), textile quality, and end-use of the fleece (Iman et al., 1992; Qi et al., 1994). Cottle (2010) indicates that roughly two-thirds of the total value of processed wool fiber, or wool top, can be attributed to mean FD. Typically expressed in micrometers (μm), also called microns, FD is defined as the thickness of a single wool fiber and is used as a primary measure of fineness. The FD largely controls if wool is spun into lower or higher quality end products. Historically, FD has not been the predominant method of wool FD, as 2 other systems were used previously (Marshall and Heller, 1915).

Fiber diameter grading systems

The first was the American Blood Grade system, developed in the early 19th century, is one of the oldest grading systems commonly used in the U.S. (Marshall and Heller, 1915). Based on the percentage of Merino blood a sheep possesses, this grading system was developed when countries began breeding native coarse wool sheep to the imported Spanish Merino, world-renowned for its high-quality fine wool. The grading system breaks down into fine, half-blood, three-eighths blood, quarter-blood, common, and braid. Essentially, coarse wool sheep crossed with fine wool sheep were expected to produce a fleece of intermediate fineness, under the assumption of incomplete dominance (Marshall and Heller, 1915). However, modern breeders understand that fineness of wool is polygenic, making breeding decisions more complex (Ma et al., 2017). Due to this deeper understanding of wool genetics, and the non-descript nature of the blood grade system, the global industry transitioned to a slightly more detailed system (Kott, 1993).

The spinning count (SC) system addressed some of the issues of the blood grade system, providing a more detailed system and a narrower range of microns within a set spin count. This approach is based more on the wool industry's processing sector, using SC to measure the fineness of the wool (Marshall and Heller, 1915). Spinning count measures how many hanks, which equal 512 m of yarn can be spun from 0.45 kg of clean wool, and the finer the wool, the more hanks of yarn that can be produced. Spin counts are typically expressed as 80s, 70s, 64s, 62s, 60s, 58s, and lower, with the greater number being the finer grade and the smaller number being the coarser grade (Kott, 1993). While the SC system provides more detail by using narrower micron ranges compared to the blood grades, it still lacked the detail and precision required by the wool marketing industry. Fleeces will likely be evaluated using the micron system in either the marketing or processing segments of the industry, though not typically used to assess fineness at the production level.

The micron grading system has become the industry standard for describing fineness when marketing wool, as it is precise and highly descriptive (Kott, 1993). The micron system achieves high precision and accuracy by measuring individual FD, meaning that a fiber with a smaller diameter is considered finer and has a lower micron value. The typical range of microns considered to be fine wool is between 22.04 μm-17.70 μm, with anything below 17.70 μm classified as superfine wool (Table 1). As the industry standard, most of the methods of measuring FD are based on the micron system and are generally presented as mean FD in order to account for the variation that occurs within the fleece tested.

Fiber diameter and variation measurement

The evaluation of FD and FD variation occurs through direct or indirect assessment (Cottle and Baxter, 2015). Direct assessment of FD measurements includes the utilization of the

Projection Microscope (PM), SIROLAN LASERSCAN (LS; CSIRO Textile and Fiber Technology, Australia), Optical Fiber Diameter Analyser (OFDA) 100 (BSC Electronics Pty Ltd., Ardross, WA, Australia), OFDA2000 (BSC Electronics Pty Ltd., Ardross, WA, Australia), and FibreLux Micron Meter (FL; FibreLux, Inc., Johannesburg, South Africa). Whereas methods to measure FD traits indirectly include the Near Infrared Reflectance Spectroscopy (NIR) and Airflow meter (AF) methods (Cottle and Baxter, 2015).

First employed in 1777, microscopy is one of the earliest methods applied to FD evaluation (Sommerville, 2007; Cottle and Baxter, 2015). Since this time, there have been many advances in microscopy methodology and instrumentation, evolving by the mid-1900s, to the PM still used today. The popularity of this application peaked from the 19th to the early 20th centuries (Sommerville, 2007). By 1950, the American Society of Testing Materials (ASTM) produced an official FD test method for the PM, and just 4 yr later, the IWTO specification for this method was published. Assessment by PM is completed by collecting short (0.40-0.80 millimeters; mm) representative fiber clips from a clean fleece and then fitting those clips to a microscope slide (Baxter, 1993). Evaluators then use a PM to assess the width of over 400 random fibers from each slide at a standard magnification level of 500x. Though determination of FD using PM seems simple, the evaluator heavily influenced this type of evaluation due to the difficulty of achieving acceptable accuracy and precision when identifying image boundaries on the microscope (Baxter, 1993; Sommerville, 2007). Additional disadvantages of PM evaluation include the amount of time and labor required to achieve precision and the associated higher testing costs. Despite these disadvantages, PM methodology remains the fundamental reference method by which all other procedures are calibrated (Cottle and Baxter, 2015). Alternate procedures were developed to improve FD evaluation's speed, accuracy, precision, and cost-effectiveness.

Starting in 1942, the wool industry adopted the AF method, which soon replaced the PM as the preferred method of FD evaluation, peaking in popularity from 1960 to 2000 (Sommerville, 2007; Cottle and Baxter, 2015). The AF method is an indirect means of evaluating fineness, calculated by measuring the velocity of airflow through a collection of wool fibers with a consistent mass and volume. Finer fibers are known to have a greater surface area than coarser fibers of a similar mass, with the surface area of these fibers being proportional to the porosity of a group of the same fibers (Sommerville, 2007; Cottle and Baxter, 2015). The standard AF method involves pumping air through a mass of fibers in an AF meter (Harwood and Smith, 2020). Using a rotameter, operators measure airflow through a mass of fibers with a specified surface area, resulting in a correlated FD calculation. Due to a proportional relationship between surface area, FD, and porosity of a fiber mass, the AF method allows for the indirect calculation of mean FD (Cottle and Baxter, 2015). A majority of the brands that produce AF meters produce 1 of 2 instrument types to evaluate mean FD. In the most utilized method, operators measure a variable rate of airflow at constant pressure (Sommerville, 2007; Harwood and Smith, 2020). In contrast, the second type of instrument has a variable pressure while keeping the rate of airflow constant. In both cases, the calibration of AF instruments requires the use of reference wool samples with known FD (Baxter, 1993).

Even after calibration, the FD measurement calculated from AF evaluation can fluctuate due to various influences. Different shape and packing variations of the fiber mass may affect the AF calculation of FD (Baxter, 1993). However, the greatest influence on AF evaluation occurs when the characteristics of the test sample diverge from the characteristics of the calibration sample. The AF method can provide only mean FD, and traits for FD variability cannot be derived from this method (Baxter, 1993; Sommerville, 2007). If test samples differ in variation from the calibration samples, this will cause fluctuations in the accuracy and precision of the AF evaluation. The AF system, despite its shortcomings, gained widespread acceptance for its low-cost maintenance upfront, easy operation, quick procedure, and low operator effect compared to the PM method that preceded it (Sommerville, 2002; Harwood and Smith, 2020). However, recent technological advancements have enabled the development of newer instruments to overtake the AF method, such as the NIR instrument, capable of measuring FD through laser optic technology.

Laser optics have been used for FD evaluation since the early 1970s, but the photometric principles of this wool assessment method date back to the 1950s (Botha and Hunter, 2010; Cottle and Baxter, 2015). Near-infrared reflectance spectroscopy uses photometric principles and can be applied as an indirect alternative to laser methods for evaluating wool FD. The NIR method uses near-infrared light rays to strike a wool fiber and measure the vibrations of molecular bonds of organic molecules (nitrogen, O, and C) with H atoms in the NIR electromagnetic region (Keogh and Roberts, 1985; Cozzolino et al., 2005). The resulting absorbance measurements from the vibrations are then used in a mathematical calculation to measure FD indirectly. Unfortunately, the NIR method has been less successful than other, more direct, photometric techniques due to the indirect nature of this procedure being less precise (Sommerville, 2007). Furthermore, more direct laser-based methods have the capability of measuring variability in addition to mean FD

Direct laser-based methods evaluate wool FD by using constant light sources in the electromagnetic spectrum and a photodetector (Sommerville, 2007). After the light beam strikes the fiber, the photodetector determines light absorption by measuring the shadow projected by the fiber (Keogh and Roberts, 1985; Sommerville, 2007). The reduction from the original wavelength to the amount that contacts the photodetector results in the FD. Though the type of measurement may vary, the evaluation principles are similar for most photometry methods. In 1971, CSIRO (CSIRO Division of Textile and Fibre Technology, Belmont, AU) constructed one of the first instruments used for direct photometric FD evaluation, the Fibre Fineness Distribution Analyser (FFDA), which involved running fiber segments past a laser beam (Botha and Hunter, 2010). Following further development of the FFDA, the instrument became alternatively known as the Fibre Distribution Analyser (FDA) just 5 yr after its initial construction. The FDA measures the light dispersion properties of wool fibers via electro-optical measurements as the fiber snippets pass through a beam of light (Botha and Hunter, 2010). The correlation between the amount of light scattered by the fiber and its fineness allows for accurate FD and FD variation determination (Sommerville, 2007). However, the FDA redesign in 1989 led to the creation of the LS instrument with a new fiber discrimination system and simplified calibration process (Botha and Hunter, 2010; Cottle and Baxter, 2015).

Due to bias in instrument readings because of inadequate fiber discrimination and difficulties in determining a calibration method for the range of FD measurements, CSIRO overhauled the FDA system, creating the LS (Sommerville, 2007). By 1992, the LS was being used commercially for greasy wool and wool top (Botha and Hunter, 2010). The LS instrument utilizes a relatively small sample of fibers that are cut to less than 3 mm long and scattered in a solution of water and isopropanol (Botha and Hunter, 2010). Gravity pulls the solution down through a pipe where a laser beam simultaneously strikes the fiber fragments. The light signals from the laser beam are carried past the fiber and then divided into two sectors (Botha and

Hunter, 2010). One part is used for the direct measurement of FD and associated variation through laser intensity. The other portion of the beam passes through the fiber discriminator for analysis, which segregates out any invalid measurements caused by foreign objects, partial and unseparated fibers before entering the computer system (Botha and Hunter, 2010). Developers of the LS fiber discriminator emphasized new fiber-optic detectors placed around the laser beam so that only single fibers which passed entirely through the beam could be analyzed (Sommerville, 2007; Botha and Hunter, 2010). The LS discrimination method produced one-sixth of the errors produced by the FFDA under the same conditions.

Calibration of the LS instrument is similar to the AF method, utilizing Interwoollabs (Interwoollabs, West Yorkshire, UK) processed reference wool (Sommerville, 2007; Mahar, 2009). Even so, this instrument requires a greater investment than AF and PM methods since sophisticated computer software and equipment are required. Due to the complex nature of the LS calibration, the calculations are performed through the LS computer with little to no operator intervention (Mahar, 2009). Sommerville (2007) suggested that the LS instrument is one of the more precise methods of measuring FD and FD variation and is known to have results similar to the PM method. Moreover, the LS instrumentation lacks portability compared to other evaluation options such as the OFDA2000.

In the 1970s and 1980s, the computer and digital technology boom contributed to the rapid development and evolution of image-analysis wool evaluation technology concurrent with the development of the LS instrument (Sommerville, 2007; Cottle and Baxter, 2015). One of the first major developments of this period was the Fibre Image Display and Measurement (FIDAM) developed by the Australian Wool Testing Authority (AWTA Ltd, Australia) in 1981. The FIDAM utilizes a low-powered microscope with an attached video camera to photograph fiber samples mounted on a slide (Sommerville, 2007). The pictures taken by the camera are run through an attached computer system that estimates the fibers' width at different points, makes corrections for out-of-focus images, and rejects images with significant errors due to lack of focus. Unfortunately, AWTA decided not to commercialize the FIDAM as CSIRO was about to release the trademarked LS machine, and AWTA wanted to focus on its commercial industry implementation (Sommerville, 2007; Botha and Hunter, 2010). Even so, due to progressions of image analysis, the FIDAM underwent further developments, eventually leading to the design of the OFDA in 1989. Differences in analysis and data collection methods distinguish the OFDA instrument from the FIDAM, despite similar design elements (Botha and Hunter, 2010).

Since 1989, three main versions of the OFDA have been produced (Cottle and Baxter, 2015). The original version of this instrument, the OFDA100, was released in 1991 and was created to evaluate small samples of clean wool fiber (Botha and Hunter, 2010; Cottle and Baxter, 2015). The OFDA100 is essentially a PM but with added benefits of computer-based image measurement. In 1995, the IWTO approved the full test specification, and in 1998, it certified the OFDA100 instrument as an official IWTO test method (Botha and Hunter, 2010). Contrary to the FIDAM method, scientists developed the OFDA100 instrument with software that promotes the intelligent selection of fibers, preventing the double counting of fibers and measurement of fibers that are stuck together (Botha and Hunter, 2010). During the OFDA100 evaluation, images of fibers are displayed on the screen, followed by the mean FD, measures of FD variation, curvature (CURV; crimp frequency) and comfort factor (the percentage of fibers below 30 μm in a sample) after assessment.

In 2000, a portable version of the OFDA100, the OFDA2000, was introduced to provide on-site fiber evaluation to the wool industry (Sommerville, 2007). The OFDA2000 instrument utilizes an automated microscope that takes snapshots of the shifting fiber sample. Unlike the OFDA100, the OFDA2000 uses full-length fiber samples, which permits the evaluation of FD along the fiber in addition to mean FD, and FD variation, and comfort factor (Notter et al., 2007; Sommerville, 2007). In just a few minutes, up to 20,000 snapshots can be taken, revolutionizing the speed with which fiber measurements can be taken (Harwood and Smith, 2020). The OFDA2000 has a higher resolution than the OFDA100, taking images at a resolution of 1 mm and then calculating the mean FD and other measurements at a resolution of up to 0.01 mm. Since the FD follows a normal distribution, the OFDA2000 can estimate the degree of variation in each fiber sample (Botha and Hunter, 2010). In the U.S., FD is now routinely assessed using the OFDA2000 in both laboratory and on-farm settings.

Following the release of the OFDA2000, the OFDA4000 was introduced in 2002 (Botha and Hunter, 2010). Based on the technology of the OFDA2000, the 4000 version can measure SL properties along with the FD properties. Processed wool top is aligned so that the length of the fiber can be measured by the OFDA4000 (Harwood and Smith, 2020). The OFDA4000 was marketed for wool processing mills and developed as a specialized instrument to measure processed wool top (Sommerville, 2007; Cottle and Baxter, 2015).

The OFDA instruments offer operator independence, rapid and simple measurement procedures, analysis for both processed and greasy wool, and a higher level of portability for on-farm measurement in the OFDA2000 version (Mahar, 2009; Cottle and Baxter, 2015). One disadvantage of OFDA machines is that they require a higher level of initial investment compared to PM or AF systems. Additionally, OFDA instruments are limited in the FD profile measurement of greasy wool, as it occurs through a series of FD measurements (4,000-20,000 measurements) along the length of the fiber at random orientations (Wang et al., 2007; Harwood and Smith, 2020). Due to this, the measurement of the diameter down the length of a single fiber does not occur. Nevertheless, according to Peterson et al. (1998), the measurement of the FD profile through multiple optic measurements with the OFDA agree with FD profile measurements down the length of a single fiber using the Single Fiber Analyser (SIFAN; BSC Electronics Pty Ltd., Ardross, WA, Australia).

The SIFAN is an alternative high-resolution measurement tool for evaluating FD (Wang et al., 2007; Cottle and Baxter, 2015). Based on the principles of the OFDA, the SIFAN instrument uses a camera to measure the width of the fibers from different angles, then stretches the fibers to determine the breaking strength (Wang et al., 2007; Cottle and Baxter, 2015). If at least 50 fibers from a staple are tested randomly, the SIFAN can also estimate mean FD within a staple. Overall, the SIFAN provides a quick alternative method for evaluating a single FD profile (Botha and Hunter, 2010).

In the world of objective wool evaluation, optical image analysis has transformed FD analysis. However, a combination of high costs of instrumentation and lack of portability remains an issue for utilization in on-farm analysis of wool (Walker et al., 2018). The FL has recently become commercially available in the wool industry, marketed as a more cost-effective, portable method of assessing wool FD according to the Technology Innovation Agency (TIA, 2016). The FL is one of the first instruments to successfully evaluate the mean FD of wool using light diffraction (Sommerville, 2007). The combination of light diffraction methodology and instrument design provides lower susceptibility to environmental inaccuracies, more cost-effective methods of evaluating FD, and higher levels of portability (Walker et al., 2018). Recently, efforts have been made to assess the accuracy and precision of the FL compared to other methods of FD evaluation (Walker et al., 2018 and 2021). In 2018, scientists compared FL precision and accuracy to the OFDA2000 across two environments. Walker et al. (2018) hypothesized that the FL would be accurate within 0.80 μm for fibers 15-25 μm in diameter based on the manufacturer's recommendations but would not harbor the precision of the OFDA2000. While both instruments had a similar level of precision when the same sample was run multiple times, the authors found an average of 0.23 μm difference in mean FD between the OFDA2000 and FL. The FL instrument's major drawback is the inability to assess measurements other than mean FD, while the other instruments and methods discussed above can evaluate FD, SS, SL, and the different types of FD variation.

Causes of fiber diameter variability

Variation in FD stems from many sources, including variations within fibers in a staple (a cluster or lock of wool fibers), along the length of the fiber, across the body, and between sheep (Iman et al., 1992). Most of the total variation of diameter resides between fibers within the staple (Cottle, 2010). Variation within the staple may occur because of differences in the mean FD of the fibers grown from primary and secondary follicles. Cottle (2010) remarked that the variation caused by the ratio of follicle type occurs more severely in some breeds than others. Some sheep exhibit such a high degree of FD variability between primary and secondary fibers that a bimodal distribution is produced (i.e., finer undercoat with a hairy coarse outer coat; Cottle, 2010). For instance, fine wool sheep have a higher ratio of secondary to primary fibers, in which a majority of the inconsistency of FD within the staple is due to the level of FD variability of the secondary fibers. Fiber diameter variability of primary and secondary fibers may also be affected during growth by variation along the length of each fiber, from skin to tip.

Variability of FD along each fiber is due to physiological and environmental influences during fiber growth (Cottle, 2010). A subset of these influences might encompass changes in nutrition, pregnancy status, lactation, and health status. Stobart et al. (1986) reported a reduced variation of FD along the fiber in flocks that had consistent nutrition compared to flocks with unreliable sources of nutrition. In stressful situations, short-term decreases in FD may occur due to energy reapportionment, causing an increase in the fiber diameter coefficient of variation (FDCV), a measure of FD variability (Cottle, 2010). Rapidly reduced FD can cause tenderness or breaks of the fiber, which can result in reduced ability to withstand the stresses of the wool processing system, increasing wastage and reducing product yield. While decreased FD during a period of stress occurs proportionally across the body, natural variation of the FD occurs across different body regions of the sheep.

In many cases, variation of the mean FD occurs across different body regions of the sheep, with the fleece becoming coarser and slightly more variable moving from the shoulder to the breech (Cottle, 2010). Stobart et al. (1986) determined that FD variation among body regions accounts for less than 15% of the total fleece variation, suggesting that breeding for decreased variation among body regions would have a minimal impact on reducing overall fleece FD variation within a wool lot. All these sources of variation contribute to the overall variability of each fleece or lot of wool, which may be described through the measurements of FD variation (Stobart et al., 1986).

Measurements of fiber diameter variation

Two different measurements, fiber diameter standard deviation (FDSD) and FDCV are used to describe FD variability (Lunney, 1983). The FDSD is a suitable measure of FD variability as the near-normal distribution of FD measurements permits the calculation of the SD using the empirical rule to estimate the dispersion of FD measurements. However, the FDSD cannot be used to compare different wool lots, as there is an association between the mean FD and SD, and when the mean FD increases, the SD also increases (Lunney, 1983). As a result, the FDSD is a less popular measure of FD variation than the FDCV.

The FDCV is expressed as a percentage and is more straightforward than FDSD as it is a simple function of the FDSD divided by the mean FD (Baxter and Cottle, 1998). Wool with a lower FDCV has less variation than wool with a higher FDCV. The FDCV is relatively independent of changes in the mean FD, suggesting that it will be a more reliable method for comparing different lots of wool (Baxter and Cottle, 1998). When processing different wool lots, the general rule of thumb is that a 5% change in FDCV is equivalent to a single micron change in the mean FD (Wood, 2003). Therefore, processing performance will be similar between 20 μm wool with 25% FDCV and 19 μm wool with 30% FDCV.

Mean FD and FD variability are exceedingly important wool production traits as global wool prices are based on the mean FD. However, price adjustments may be made based on factors such as SL, an aspect of wool production that is significant in all sectors of the wool industry (Rogers and Schlink, 2010). Staple length is of tremendous importance to the processing side of the industry due to its effect on processing performance, end-product quality, and value.

Staple Length, Strength, and Variation

Staple Length

Staple length is a visually appraised length measurement that provides a simple indication of fleece value and quality which can be used for industry marketing purposes (Wilson and Morrical, 1991; Cottle, 2010). Moreover, SL is an important indicator of the processing and product potential of wool based on the strong association between SL and the mean fiber length of top when considering wool of sufficient soundness or tensile strength (Lupton, 1987). Staple length has historically been categorized into three primary length divisions, staple, French combing, and clothing, with staple being the longest and clothing being the shortest (Lupton, 2015). However, SL is typically described in international wool sale lots using specific length measurements (i.e., mm) as the length divisions may be misunderstood for two reasons. First, the use of length divisions can be confusing as a staple in the U.S. can be used as a measurement of wool length or to describe a cluster or lock of wool fibers. Second, length divisions may not be useful as every wool mill has varying length requirements based on the processing system used and end-product produced.

Staple length has a significant impact on determining the processing route of a fleece in manufacturing, as spinning speeds, yarn count, and yarn quality are all affected by the fiber length of top (Lupton, 1987). For example, a high percentage of short fibers in wool that has not been expelled during processing can lead to pilling, hairiness, unevenness, fiber shedding, and an overall loss of quality in garments and yarn (Wood, 2003). On the other hand, longer fibers tend to generate more robust, uniform yarns while also tending to pass through processing machines with superior efficiency (Wood, 2003; Cottle, 2010). Even so, overly long fleeces may not be accepted by some processors due to issues with carding, the process by which fibers are aligned into a continuous parallel strand, as higher levels of breakage occur due to the force required to untangle the longer fibers. Due to processing restrictions, fleeces with an intermediate SL are higher value than those with short or extremely long staples.

Genetics, nutrition, and external factors play critical roles in wool growth and whether SL meets the optimal length desired by wool processors at the time of shearing (Rogers and Schlink, 2010). Through genetic selection, producers can improve the mean SL of their flock based on the moderate to high heritability of SL and its correlation with other traits (Lupton, 2015). Thus, if producers select for increased FW, mean SL may increase, but if decreased FD is selected, mean

SL may decrease (Lupton, 2015). Nutrition and feed intake can also impact the mean SL of a fleece, as increased nutritional intake will encourage fiber growth through enhanced cell proliferation (Rogers and Schlink, 2010). Some nutrients will have more significant impact on fiber growth than others. For example, deficiencies in amino acids, Cys or Met, will stunt wool growth, while additional supplementation of Cys or Met will facilitate growth (Reis, 1979; Rogers and Schlink, 2010). Staple length may also be impacted by a variety of external factors such as, seasonal variation of fiber growth, stresses on the sheep during the wool growth cycle (drought or lambing), and even when shearers may cut wool at different lengths. Many of these impacts on SL can manifest as low SS or a break in the staple.

Staple Strength

Staple strength measures the force needed to break a standardized wool sample and indicates the individual wool fibers' ability to be processed without dividing (Cottle, 2010; Nolan et al., 2013). The SS measurement is defined by four strength groups measured in N per kilotex (ktex): 1) sound (30 N/ ktex and greater), 2) part tender (approximately 20 N/ ktex), 3) tender (approximately 15 N/ ktex), and 4) rotten (10 N/ ktex). Though buyers may not pay more for wool with satisfactory SS, they will significantly reduce the price for weak, unsound wool, as SS indicates how the wool will behave in a top-making system. Staple strength levels differ partly due to genetic effects but are mainly due to fluctuations in the wool growth cycle, potentially altered by changes in flock health, illness, stress, and environmental sources affecting the availability of nutrients partitioned for wool growth (Lupton, 2015). During the wool growth cycle, environmental, nutritional, or lambing stresses can decrease FD growth rapidly causing a seasonal break in the wool (Lupton, 1987; Cottle, 2010). The break can occur at any point along the wool staple, depending on where in the wool growth phase the stress occurred. In low SS wool, the break's position is a significant factor in determining the value and processing system to which wool will be allocated since some positions are more detrimental to processing efficiency than others (Wood, 2003).

Fleeces that break near the staple tip will produce a high percentage of noilage, or short fiber segments, which are expelled from the usable product during processing (Wood 2003). Cottle (2010) noted that noilage may be used to make carpeting or felt materials, but the byproduct has no place in the manufacture of finer goods, such as wool suits. Alternatively, the wool may suffer from a midpoint break near the center of the staple, which is generally caused by environmental stress during fleece growth (Nolan et al., 2013). A midpoint break will have a lower mean fiber length after processing but may not result in as much waste as a tip break (Wood, 2003). Wool with sufficient SS will be better able to withstand the stresses of the manufacturing process, passing through processing with minimal breakage.

Staple Length and Strength Variation

Like FD, SL and SS have components of variation both within and between fleeces (Cottle, 2010). Staple length variation within fleeces occurs through inherent or exogenous sources. Staple length and SS variation due to inherent sources include variation between body regions, for instance, wool from the shoulder is longer than wool from the sheep's britch, or hind end, while the belly has the shortest SL on the body due to compression and matting. Staple length or SS variation due to exogenous sources includes the quality of shearing (e.g., not cutting next to the skin or producing a high percentage of second cuts; Cottle, 2010). The changes in SS are typically a function of fluctuating FD along the staple, which would occur over the entire body. Decreasing FD reduces the thickness of the fiber, making it thinner and weaker, whereas increasing FD will make for a stronger, thicker fiber (Cottle, 2010). However, additional environmental effects may cause regional changes in SS, such as wool weathering on the back, causing staples to weaken at the tip. The range of mean fleece SL would usually be between 35 and 40 mm within a properly classified group of fleeces. Since sheep within a flock are exposed to similar environmental stressors, which can mask genetic diversity, relatively similar SS levels are expected (Cottle, 2010). Nevertheless, in a flock, the mean SS values can vary by up to 50 N/ktex. Physical stressors, such as illness or fever, typically cause variability of SS in individual sheep but not the entire flock. (Cottle, 2010). Producers may control some of the variation in their wool clip through the classification of each fleece for mean SS and SL. Unfortunately, the physical assessment of SS through classing is not as precise as automated testing, limiting the amount of SS variation that can be removed from lots. Though SL variation can be reduced through classing, fiber length variation increases by 500% during processing since even sound wool can exhibit fiber breakage, therefore, reducing fiber length variability of top by less than 20% (Cottle, 2010).

Fleece Weight

The U.S. commercial wool sector markets wool on a per-pound basis, with discounts and premiums based on FD and other wool characteristics, implying heavier FW is exceptionally advantageous to U.S. producers (Wilson and Morrical, 1991). Industry marketing and selection divide FW into two different categories, GFW and CFW.

The GFW refers to the weight of a shorn fleece, which includes all fiber components, lanolin, dirt, grease, and VM, and may contribute to an animal's genetic potential for wool production (Rogers and Schlink, 2010). Measured in kg, people can quickly obtain GFW using a set of scales, making it one of the easiest measurements to obtain. Botha and Hunter (2010) noted that greasy wool bales might contain up to 50% foreign matter. For the producer, GFW is a trait of economic significance that can be quickly and accurately measured; however, CFW is of much greater economic importance in total commercial value of the fleece (Johnson and Larsen, 1978).

Clean fleece weight can be defined as the fleece's weight after removing all non-fiber substances. The original method of obtaining CFW was to scour whole fleeces individually, but this method is labor-intensive and expensive (Johnson and Larsen, 1978). Instead, rapid and accurate estimation of CFW can be obtained by examining a representative core sample from a wool fleece. In a core test, several evenly spaced tubes are driven through a compressed wool bale or fleece to obtain a representative wool sample (Cottle, 2010). Core testing of fleeces may be performed by either hydraulic or hand coring equipment. Primarily used in the 1950s and 60s, hand coring is performed by the operator manually driving the sharp metal cores though bales of wool samples. Hand coring only penetrates half-way through bales meaning that more hand cores need to be taken than would have using a hydraulic core machine, meaning cores using the hydraulic machines are typically quicker and easier to obtain. Hydraulic core sampling is commonly used to obtain accurate measurements of FD, VM, YLD, and CFW (Roger and Schlink, 2010). From core samples, YLD and CFW can be determined by scouring the greasy samples to remove the non-fiber elements, resulting in a percentage YLD, which can then be used to calculate CFW. Unfortunately, this cheaper, more efficient method of obtaining CFW has not prompted producers to obtain YLD or CFW measurements with GFW remaining the more commonly reported trait (Notter and Hough, 1997).

Fleece yield

Fleece yield is the percentage of clean wool fibers expected to be usable after scouring a greasy fleece (Cottle, 2010). Although producers are paid by the pound on a GFW basis, the

YLD plays an important role in pricing since it indicates CFW, determining the commercial value which drives the GFW price. A fleece with a higher percentage YLD will bring a better price when being compared to similar weighing greasy fleeces, since more clean fiber will be available for processing (Rogers and Schlink, 2010). Fleece yield is calculated through the removal of all non-fiber contents from a core sample, and then calculating a percentage based on the weight lost between the greasy and clean samples (Lupton, 1987). In some cases, the tested YDL may differ from the actual processing YLD due to variation among the wool lot tested.

There is variation of YLD within fleeces, between fleeces, and amongst wool flocks, with significant variation determined by the environmental contents, such as VM and dust (Thornberry and Atkins, 1984). Vegetable matter and dust tend to cause more variation within a fleece and amongst flocks rather than between fleeces from the same flock. The YLD variation within a fleece due to VM and dust are highest in the ventral and ventral-posterior sites, as these areas tend to have more direct contact with the ground. The percentage YLD also tends to decrease as dirt and VM increases from the body's anterior to posterior regions (Thornberry and Atkins, 1984). In contrast, YLD variation among wool flocks due to VM and dust may occur due to different management and environmental conditions of different flocks. Sheep raised in South Dakota, for example, tend to be exposed to less dust and VM than sheep raised in West Texas. Additional variations in YLD can be caused by naturally occurring non-fiber substances, such as lanolin, a fatty substance secreted by sebaceous glands, and suint, a salt-like substance exuded from sweat glands (Rogers and Schlink, 2010). Thornberry and Atkins (1984) found that variations in YLD due to lanolin and suint within individual fleeces were less variable than variations between fleeces. There is greater variation between fleeces because each sheep produces a unique level of lanolin and suint based on a combination of genetics and environmental factors (Gillespie, 1948). While non-fiber components largely determine YLD and the variation of YLD, fiber characteristics may also play a role.

Fiber traits such as color, staple density (STD), medullated fibers, and wool crimp can also influence fleece YLD. While most non-fiber components are removed during scouring, wool may still retain medullated fibers and unscourable color, which can be detrimental to the value of wool top if not removed (Simpson and Crawshaw, 2002; Cottle, 2010). Therefore, the presence of a high percentage of medullated fibers and unscourable color contributes to the wastage of product during processing, and thus impacts the YLD. The crimp may also have effects on YLD during processing, as wool with a higher crimp frequency may have slightly higher processing losses due to increased breakage when attempting to detangle and align the fibers for further processing (Cottle and Baxter, 2015). In comparison, STD influences the YLD prior to processing, as fleeces with higher STD tend to be more resistant to environmental influences and may have reduced dust and VM contamination as an effect (Lockart and Philpotts, 1954). By improving wool style aspects such as color, crimp, and STD, through proper wool preparation methods, wool YLD can be improved (Lupton, 2015).

Wool style

Wool style includes color, crimp definition, staple structure (staple tip weathering and shape), STD. Generally, these characteristics make up greasy wool's appearance and facilitate description and classification of wool (Cottle and Baxter, 2015). Though style grades are used for wool description in the international wool market, the U.S. industry typically uses wool character to describe the color, crimp, and general condition of domestic wool. All wool style traits were evaluated subjectively but advancements in wool metrology have enabled objective evaluation of several wool style traits. Despite this, the implementation of a single instrument to collectively measure style has not been achieved (Cottle and Baxter, 2015). For marketing and reporting purposes, the style classification is broken down into 7 grades (from highest to lowest quality) including: choice, superior, spinners, best top-making, good top-making, average top-making, and inferior (Macpherson, 2012).

Style traits can be influenced by environmental and genetic factors (Cottle and Baxter, 2015). The environment strongly influences the characteristics of staple tip weathering and dust penetration (DP), but producers can mitigate these effects by protecting the fleece from environmental damage (Hatcher et al., 2008). In contrast, crimp definition and STD are primarily determined by genetics/breed components (Wood, 2003; Cottle, 2010). Wool color is unique within style in that is influenced by genetics and environment.

Color

In most fine wool sheep, such as the Rambouillet and Merino breeds, the wool color can vary from bright white to soft yellow, which is desirable for processors because the fibers will take dye better (Rogers and Schlink, 2010). Scoured wool that is white in color will have a greater dyeing capacity, meaning it is not limited by poor color uptake, but can be dyed to a wide range of colors (Wood, 2003). Conversely, stained, or dark colored wool will have a low dyeing potential and will be limited to specific colors, such as dark shades, due to insufficient absorption of the color. In wool production, especially fine wool production, discounts increase linearly with greater discoloration of fleeces (Mortimer, 2009).

White shaded fleeces are more susceptible to discoloration, which may stem from oxidation or environments where high humidity, heat, and stress levels may increase suint levels and bacterial activity (Rogers and Schlink, 2010). Oxidation of wool may occur when ultra-violet light and O interact with amino acids in wool fibers, such as Cys and Trp, causing discoloration of varying shades of yellow (Cottle and Baxter, 2015). Oxidative discoloration can also occur in finished wool products that may experience high levels of ultra-violet light exposure. A more intense level of discoloration can be attributed to increased heat and humidity, which results in increased suint levels and increased bacterial activity producing higher concentrations of aldehydes (Dyer et al., 2007; Rogers and Schlink, 2010). Aldehydes react with the present amino acids to produce larger chromophore (pigmented molecules) concentrations, mainly phenazines, ranging from yellow, blue, pink, to red, and can cause unscourable discoloration of wool. Still, whether through bacterial, oxidative, or other means, discoloration of clean wool may occur throughout the production cycle (Rogers and Schlink, 2010).

Besides discoloration, color issues in wool may also arise from naturally colored or stained fibers, which primarily occur during wool production and preparation. Natural-colored fiber contamination may occur when a white flock is in contact with a dark-pigmented sheep, when aging sheep produce dark patches of wool, or through flock genetics (Simpson and Crawshaw, 2002; Cottle, 2010). The presence of natural-colored fibers can cause contamination during processing if not addressed during breeding, selection, and shearing. Stained wool from urine or feces is dark yellow to orange and generally transpires through the failure to properly remove the stained wool during skirting, the inadequate removal of wool around breach during shearing (crutching), or poor pen hygiene. With either naturally colored or stained fibers, the dark pigmentation of fibers will not take dye correctly, and thus, will stand out at the end of the top-making system (Simpson and Crawshaw, 2002). The contaminated fibers must be completely removed in lighter shades of dyed wool, or a wool mill technician must meticulously remove each dark fiber. In such cases, high levels of contamination will result in heavy discounts on the value of wool but may be prevented through proper management.

Management of undesirable wool color in a flock must begin at the producer level. For instance, skirting is a popular method of removing significant portions of pigmented or discolored fibers from fleeces, resulting in improved flock color (Cottle, 2010; Cottle and Baxter, 2015). Prior to shearing, proper crutching and pen maintenance can be utilized to reduce the amount of urine-stained fiber, bacterial growth, and water damage associated with wet climates. In addition, wool color issues may be partially addressed with critical selection and breeding, though effects may not be removed entirely due to environmental influences (Lupton, 2015). Selection against wool color may occur through correlated traits, as fleeces resistant to discoloration also tend to have lower suint levels, lower FD, and a higher YLD (Mortimer, 2009). Though alternative indicators of acceptable wool color are available, the accurate evaluation of fleece color and its cause remains necessary for marketing and selection purposes. Discoloration occurring during the storage of shorn wool can be addressed by moving wool to a dry storage area out of direct light to avoid long-term ultra-violet light contamination (Cottle, 2010). Unfortunately, the poor relationship between clean and greasy wool color and the fact that discoloration can occur during all stages of production can make the objective evaluation of fleece color difficult (Cottle and Baxter, 2015; Lupton, 2015). While Australia and New Zealand have successfully implemented objective methods of evaluating wool color in their commercial industries, the U.S. wool industry has yet to do so, instead utilizing mainly visual assessment.

In 1988, the IWTO drafted an international test method that utilized spectrophotometers calibrated using certified ceramic color tiles (Cottle and Baxter, 2015). The spectrophotometer aims a beam of light at a sample of wool and the light is either reflected or refracted. The light reflected by the fiber sample includes diffuse and specular light, which are used to determine the proportion of specular light used in color value calculations (Cottle and Baxter, 2015). Color value calculations are divided into 3 zones of the visible spectrum: red/orange, green/yellow, and blue/indigo/violet (Simpson and Crawshaw, 2002; Cottle and Baxter, 2015). The green/yellow zone describes fleece brightness, while green/yellow minus blue/indigo/violet describes wool yellowness. Wool color is determined by its wavelength reflectance, with white wool having a higher reflectance of all wavelengths compared to more yellow pigmented wool, which will have a lower reflectance of blue/indigo/violet wavelengths (Cottle and Baxter, 2015). Alternatively, if reflected wavelengths in the green/yellow zone increase, wool brightness will also increase. This test method allows for accurate measurement of wool color from both a clean and greasy standpoint, however, it does not account for changes in wool color that occur throughout storage and processing (Cottle and Baxter, 2015). Nevertheless, the Australian Wool Exchange Limited (AWEX) has developed a color grading system for marketing and appraisal of unscourable discoloration in greasy wool (Mortimer, 2009). The AWEX system classifies unscourable wool color into three distinct categories, light, moderate, and heavy, with an additional classification for bacterial discoloration and water staining. Wool color remains a vital aspect of the fiber processing sector; however, foreign markets have expressed concerns about the suitability of U.S. wool due to the lack of objective evaluation of wool color and contamination introduced at the producer level (Lupton, 2008, 2015). Due to the detrimental effects dark fibers, staining, and ultra-violet exposure can have on wool textiles, color is a critical element of wool style and overall production (Mortimer, 2009).

Crimp

Crimp is defined as the natural waviness of a fiber, which can be evaluated visually or objectively through wave frequency measurement (Cottle and Baxter, 2015). It is possible to estimate crimp frequency by evaluating CURV, a measurement of the curve of each wave within a fiber that may be evaluated by either the OFDA or LS instruments to determine a measure of degrees per millimeter (°/mm; Rogers and Schlink, 2010). For instance, a 1 mm fiber with a CURV value of 180°/mm will form a half-circle, whereas if the 1 mm fiber is straight, the CURV will be 0. The CURV significantly influences the softness, handle, and other characteristics of finished wool products, but is highly dependent on processing settings and the product produced (Cottle and Baxter, 2015). Wool with a higher CURV tends produce stiffer textiles with increased bulk and can improve the softness of knitted fabrics (Wood, 2003; McGregor et al., 2015). Wool with higher CURV may also generate higher noilage production and lower yarn strength, likely due to the increased bulk creating stronger interactions with the carding and combing rollers (Lupton, 2015). In comparison, lower CURV wool may be more prone to entanglement and felting during the scouring process, and if not addressed may have negative effects on fiber length. Wool with lower CURV is also more likely to maintain a smooth, uniform yarn due to superior spinning that is best used in the worsting process to produce a thin, flexible, softer handling fabric (Wood, 2003). When it comes to product quality, higher CURV is generally better suited to yarn intended for knitwear and blankets, while low CURV is better suited for yarn intended for suits and high-end worsted apparel (Cottle and Baxter, 2015).

Crimp definition is also an influential aspect of crimp and can be partially evaluated by the objective measurement of the CV of CURV (Rogers and Schlink, 2010; Macpherson, 2012). Crimp definition largely depends on breed type and the consistency of nutrition throughout the year (D'Arcy, 1990). Desirable crimp definition is well-defined, with evenly organized fibers that may indicate growth of uniform fibers in both FD and SL than that of poorly defined fleeces. Due to the uniform alignment of fibers, wool with good character will also run through processing smoother (D'Arcy, 1990). In contrast, wool with poor character will have little distinction of crimp due to fiber disorganization, be rougher handling, and exhibit greater variability in SL and FD. Fleeces of good crimp definition should not be mixed with wool of poor crimp definition, as the reduced crimp quality will negatively affect the overall style (Macpherson, 2012).

Staple density, dust penetration, and staple weathering

Staple density, defined as the proximity and number of wool fibers within a given surface area, is another aspect of wool style primarily determined by genetics (D'Arcy, 1990; Cottle, 2010). For the most part, sheep with higher STD produce heavier fleeces that are more resistant to environmental influences and easier to process (Lockart and Philpotts, 1954; Rogers and Schlink, 2010). Conversely, lower STD can contribute to environmental degradation or weathered tips in wool that can increase noilage during processing. Additionally, the STD affects YLD, with lower STD fleeces having lower YLD and higher amounts of VM (Lockart and Philpotts, 1954). Fleece density can be assessed visually through feel and appearance, however, there is no commercially available objective test method to quantify STD. Even so, traits such as character, VM content, and DP may indicate the STD (D'Arcy, 1990).

The DP serves as an indicator of the STD since low-density fleeces will have higher amounts of DP than high-density fleeces (Rogers and Schlink, 2010). Dust penetration refers to the amount of solid dirt and dust that penetrates down into the staple beyond the wool tip (AWI, 2013). Despite the lack of an objective test for DP, AWI developed a visual scoring guide for DP. The scale ranges from 1 to 5, with 1 being almost no DP within a staple and 5 being more than 70% DP (AWI, 2013). High levels of DP occur in conjunction with increased weathering of wool tips, causing increased noilage in processing (Doyle et al., 2021). Prior to the commercialization of objective YLD measurement, DP of the staple was also used as an indicator of YLD, with higher levels of DP indicating lower YLD in fleeces (Rogers and Schlink, 2010). Although almost all the dust within wool is removed by scouring and processing, environmental degradation remains, resulting in noilage and lower fleece YLD.

Although some wool style traits may be of indirect economic importance, they all affect the processing capacity and efficiency and may affect traits directly impacting wool production. For this reason, optimal selection for wool production requires consideration of traits that may not appear to be directly related to improving desired traits, but are nevertheless influential (Roger and Schlink, 2010).

Fiber diameter, FDCV, SL, SS, GFW, CFW, YLD, and style attributes all influence the value, processing performance and end-product quality of wool (Cottle, 2010). For instance, wool buyers will apply heavy discounts to a wool bale with a consistent tip-break because the bale will produce excess noilage during the carding process, making wool processors less inclined to purchase it. Many of the discounts incurred due to poor wool quality can be directly addressed through proper management and wool preparation, maximizing the profitability of wool production.

Wool Harvest Preparation

Improving the quality of a producer's wool crop, or clip, begins with proper wool preparation. Since wool is a global commodity, improved wool clip quality through appropriate preparation may indirectly promote market conditions for American grown wool by increasing the wool marketer's and processor's interest in U.S. wool. Critical control points of wool preparation include preparation of wool for shearing and preparation of the wool clip for marketing, both of which can improve quality of the overall wool clip (ASI, 2014).

Shearing Preparation

Wool harvesting, or shearing, marks the end of the wool growth cycle and the beginning of wool marketing. Shearing procedures, in general, have changed relatively little over time and are similar throughout the global industry (Lupton, 2015). In contrast, shearing facilities in the U.S. vary tremendously, ranging from permanent buildings used only once a year to portable shearing trailers owned by shearing crews allowing mobility from operation to operation. Each type of shearing area can expose fleeces to varying degrees of weather, VM, dirt, dust, and other sources of contamination. Fortunately, by following a few preparation practices before and during shearing, wool producers can take several factors into account to maintain a quality wool clip.

The preparation process begins approximately 12 h before shearing when the sheep are gathered and held in a clean pen to maintain dry sheep and prevent further contamination from dust and VM (ASI, 2014; Lupton, 2015). In the same timeframe, withholding both feed and water may partially prevent urine stain and can keep the shearing floor clean and dry. Prior to shearing, flocks should also be sorted into groups, typically based on breed and age, such as lambs, yearlings, rams, and ewes to create more uniform groups, or lines, of fleeces (Lupton, 2015). Pigmented and hair sheep should be moved away from the main flock and confined to a separate set of pens. Sheep with any pigmented fiber and hair sheep (if necessary) should only be shorn after sheep with white wool have been shorn (Lupton, 2015). These steps reduce possibilities of further contamination of white wool. Though individual fleeces can be removed from the floor in only a matter of seconds, there may still be high levels of exposure to dirt, grease, and VM during shearing. To minimize exposure during shearing, the shearing floor, typically made up of wooden boards, should be swept and kept clean at all times (Lupton, 2015).

Further contamination or poor wool quality can be addressed prior to baling through wool clip preparation.

Wool Clip Preparation

Within the U.S., there are 2 quality preparation techniques used after shearing is completed, bellies out untied (BOU) and full table skirt (FS; Lupton, 2015). The BOU procedure involves removing the belly wool from the fleece during shearing and keeping it separate from the main wool line because belly wool is often short, low yielding, and contains a large amount of contamination. If necessary, the remaining part of the fleece may be lightly skirted to remove any stain or discolored wool, however in most cases, it is rolled skin side out and placed in a wool bag (Lupton, 2015). The BOU method can remove a substantial amount of lower quality wool from a fleece, but wool handlers picking up fleeces must be well versed in recognizing and removing low-quality pieces (offsorts) of the fleece quickly (ASI, 2014).

In comparison, a FS goes one step further than BOU (Lupton, 2015). In the FS method, the fleece is picked up by the leg sections and thrown, shorn side down, onto a skirting table where wool handlers remove or skirt out any inferior wool from the majority of the fleece while rolling it up shorn side out. Throwing the fleece onto the skirting table allows the skirters to easily examine all portions of the fleece for foreign objects, such as skin and polypropylene, and allows for second cuts and loose locks to fall out (Lupton, 2015). Before the skirting begins, however, the wool handler must evaluate the operation's management practices and environmental conditions to assess the average quality of the wool clip and the level of skirting required (ASI, 2014). After this evaluation, wool handlers work to minimize the amount of skirting that occurs so that the average quality wool stays with the fleece. Skirting is a simple process if handlers follow a few general rules (ASI, 2014). Similar to the BOU method, the first practice of skirting is to remove the belly wool and place it into a separate line; this occurs while the sheep is being shorn. Then, after the fleece has been thrown onto the skirting table, the wool handler will spin the skirting table, allowing quick removal of heavy stain and poor-quality locks, or tags. Any of these off-sorts will be moved to separate lines (ASI, 2014). In order to reduce contamination of the main line of wool, any fleece containing pigmented fibers is removed and bagged separately from the white wool. The skirting process is overseen by wool classers to ensure that offsorts are sufficiently removed and placed in the proper bags ad that skirters do not remove too much of the quality wool. A properly skirted fleece may have an increased average YLD and fiber length of top with a simultaneous decrease in VM, noilage, and colored fibers (Kott et al., 1992).

Following skirting, fleeces are evaluated and classified into uniform fleece lines by a wool classer (NRC, 2008). Wool classing is the initial process of evaluating fleeces according to characteristics such as FD and SL to create lines of standard quality wool (Lupton, 1992, 2015). Unlike skirting, wool classing requires the specialized training and knowledge of a wool classer. Wool classers' primary responsibility is to sort fleeces into uniform lines of similar types while maintaining as few lines as possible and minimizing levels of contamination among lines (Lupton, 2011, 2015). When there is a sufficiently sized wool clip, a well-trained classer can use wool handle (the feel of wool) and visual cues to reduce the FD and SL variability between lines (Cottle, 2010). For instance, both coarser fleeces and short or tender fleeces are typically classed into different wool lines, which reduces the variability of each wool line. However, wool classers should avoid the unnecessary creation of lines; the creation of too many lines can actually reduce profitability and efficiency (ASI, 2014; Lupton, 2015). In order to avoid the unnecessary creation of lines while maintaining uniformity, the general rule of thumb is to ensure that the variation of one line does not exceed two SC grades on either side of the average. For example, fine wool breeds may have a line that ranges between 70s to 62s with an average of 64s, depending on the majority of the wool clip. This preparation method originated in Australia but has since been adopted by some U.S. shearing crews to improve buyers' confidence and profit potential in fine wool production, the type of production for which it has proved most effective (Lupton, 1992, 2015). For a wool classer to produce lines that appeal to wool buyers, it is necessary to communicate with the producer how their wool is intended to be marketed, since each channel may have different specifications. For instance, while fine wool is evaluated based on FD, SL, SS, color, and VM, carpet wool is typically classed based on color issues and fleece tenderness (Simpson and Crawshaw, 2002).

Apart from classing, wool classers must properly pack and label wool bags according to the wool line and accurately record the wool clip. The ASI Wool Classing Line Standards were developed as a standard method for wool classers to organize and label wool bags (ASI, 2014). These standards are also utilized to keep physical records of wool bales. For example, ‘A’ represents a bale containing the main line of wool with 12 mo of growth, and ‘A-2’ represents a bale containing the tender or short end of the wool clip (ASI, 2014). In general, the wool classer is responsible for overseeing all wool handling once shorn and must be capable of fulfilling the tasks required at any wool handling station. Once the wool is baled and accurately labeled and recorded, the next step in clip preparation is objective testing of the wool bales.

Ideally, wool clip preparation will result in as few uniform lines as possible that will be combined into larger wool lots which will run through processing efficiently, maximize producer returns and boost buyer confidence (ASI, 2014). Large lots of wool are more likely to be bought by wool buyers than several smaller ones because they tend to be more cost-effective and may fill buyers' orders from processors faster. It is also more economical for the producer to have larger lots, as marketing charges are calculated on a per-lot basis. Moreover, larger wool lots lead to lower associated selling costs, such as those from wool testing (ASI, 2014).

Wool Clip Testing

One of the last steps before wool is marketed is the objective testing of the bales. Objective testing is a scientific assessment that provides producers, processors, and marketers with the opportunity to make decisions without bias (Lupton, 2015). The majority of wool traits can be evaluated via objective measurement, with the exception of some minor traits, such as style. Producers can use objective measurements of raw wool to establish and monitor flock selection goals (ASI, 2014). Moreover, objective measurement provides producers with more information about the quality and quantity of their wool clip, so their wool can be marketed more effectively. Wool processors may also utilize objective testing to better understand the suitability of the fiber for different end-product uses (Harwood and Smith, 2020). To gain an accurate view of any wool characteristic, the sample used for wool testing measurements needs to represent the whole (i.e., the entire wool bale or individual fleece; ASI, 2014). Core and grab samples are currently the main sample types taken in the global wool industry, which accurately represent the bale or fleece.

Core Testing

Core testing is a standardized practice widely used in the wool industry to obtain samples of greasy and clean wool (Cottle, 2010; ASI, 2014). The samples can be used to measure most of the major wool traits, except those related to length, as the coring machine only cores samples up to a specific size based on centimeters (cm; i.e., 5.08, 2.22, or 1.27-cm samples). Core samples are collected, either by hand or hydraulically, by forcing several sharp metal tubes through a compacted wool bale or bag, with each core representing one sample from the bale (Cottle, 2010). The ASTM has published a standard method for taking core samples, which includes a description of the equipment, the number of bales to be sampled per lot, and the number of cores required per bale or bag (Lupton, 2015). In the ASTM method, the maximum lot size was 25 bales, because the number of cores required for bale is dependent on the lot size, and multiple entries with the coring machine could produce significant damage to the wool. Wool testing agencies have, for the most part, abandoned the ASTM standards based on the number of cores per bale or bag (Lupton, 2015). Instead, wool testing labs prefer to test every bale relative to the total number of bales in a lot. The ASI provided alternative testing standards not covered by ASTM, by assigning the number of cores required per bale by the number of bales in each lot (ASI, 2014). For instance, using a 5.08 cm coring machine, ASI recommends only 3 cores per bag in small lots of only 6 to 9 bags, whereas only 2 cores per bag are needed in large lots of 20 to 40 bags. According to ASI and IWTO sampling methods, a simple calculation can derive the minimum number of cores per bale needed to achieve precision of ±1% of the content of clean wool specified at a 95% confidence level (ASI, 2014; Lupton, 2015).

Portable coring instruments used in the U.S. typically have metal tubes with 1.27 cm or 5.08 cm diameters (ASI, 2014; Lupton, 2015). These instruments were traditionally used on burlap sacks. In the last 20 yr, wool packaging has changed from soft, cylindrical burlap sacks to rectangular nylon bales since wool can be packaged more densely, making it easier to ship (ASI, 2014; Lupton, 2015). As packaging has changed, many wool testers have shifted to hand coring machines with 2.22 cm tubes to follow the ASI and IWTO regulations. Lot core samples are packaged in sealed bags and are sent to fiber testing laboratories for further processing and analysis upon completion of core sample collection (Lupton, 2015). Since 1.27 cm and 2.22 cm samples are smaller and easier to manage, they can be tested without further subsampling, but 5.08 cm samples must be resampled with a smaller coring machine before measurements can be taken. In any case, both hand and hydraulic coring techniques will follow IWTO and ASI Wool Classing Line Standards recommendations on the precision and probability levels to decide how many core samples should be taken from each bale (Steere, 2009).

Grab Sampling

As core samples are not suitable for testing fiber length traits, grab sampling can be used as an additional sampling method to test SL and SS (Cottle, 2010). Additionally, grab sampling may be used during the sale of wool through visual appraisal with no objective measurement. Grab sampling may be performed manually by removing whole, undamaged staples from random locations in the wool bale or hydraulically using a grab jaw that removes wool tufts of 150-350 g from different locations around the wool bale (Cottle, 2010; Lupton, 2015). Either method requires samples to be taken from each bale in the lot (bales must be similar in mass), using the same technique. Based on IWTO testing methods, a minimum of 20 samples should be taken from each sale lot; however, to protect the integrity of the wool clip, only two suitable samples may be taken from either side of each wool bale in the sale lot (Cottle, 2010). Under the IWTO guidelines for measuring SL and SS using grab samples, a minimum of 60 representative samples should be subsampled from the combined lot sample, including any second cuts drawn (Cottle, 2010).

Regardless of the sampling method, both produce representative samples that can be sent to wool testing laboratories worldwide to accurately analyze wool traits (Cottle, 2010). Wool testing machines and procedures include those previously mentioned including the OFDA2000, LS, FL, the YLD testing procedure, and the SIFAN. By objectively testing wool clips before purchase, wool producers and marketing agents may evaluate wool lots without bias, reducing risks associated with buying and selling wool, such as the evaluation of grease price or accurate description of the wool lot (Lupton, 2015). Moreover, objective wool testing has paved the way for further globalization of the wool industry as it provides a common language that is used throughout wool marketing.

Wool Marketing

There are three primary levels to wool marketing: the producer or wool operation the marketing agent's central storage, and the final sales location (Lupton, 2008, 2015). In most cases, wool moves from the producer's shearing floor to a central storage facility, where the primary marketing agent will offer the wool for sale to several buyers using different sales methods. Generally, the primary marketing agent gains commissions on wool sales either to a secondary buyer or directly to the processor (Lupton, 2008, 2015).

Marketing Channels

Generally, there are four main channels used in U.S. wool marketing: the producer, wool pools (WP), fiber cooperatives (CO-OP), and wool warehouses (WW; Lupton, 2015). With the exception of producer marketing, these systems aim to provide wool buyers with more appealing purchasing options by providing larger quantities of wool that meet their buyer's unique specifications, such as a certain level of uniformity (NRC, 2008). Different wool marketing systems may focus on either direct or indirect marketing to buyers. Direct marketing refers to selling wool directly to consumers, common in niche markets such as the hand spinning industry (Schoenian, 2020). On the other hand, indirect marketing focuses on selling raw wool to secondary marketers but not to the end-user. While WP, fiber CO-OPs, and WW primarily focus on the indirect marketing of raw wool, producer channels vary, with some focusing on both direct and indirect marketing (Schoenian, 2020).

Producer

Marketing by producers can vary greatly, from producers with small or inferior wool lots who may offer the wool to shearers as partial payment for their services, to growers whose high-quality wool is marketed directly to wool mills (Lupton, 2015). Producers may choose to use direct marketing, which often involves selling whole fleeces to hand spinners, weavers, and other fiber tradespeople that produce yarn by hand, though some producers with larger clips may market their wool clip directly to mills. All fiber tradespeople have different preferences for wool color and style, but all desire wool free of VM and contaminants (Schoenian, 2020). Therefore, wool marketed directly to fiber artisans should be skirted, with all belly wool and stained wool removed.

Traditionally, producers with larger clips may negotiate sales prices with order buyers or independent warehouses (NRC, 2008). In these situations, it is critical for the producer to have built a reputation for high-quality wool with potential buyers. Moreover, accurate records of market prices and objective measurements are essential for producers to make informed business decisions (Lupton, 2015). However, wool buyers' preference to bid on large lots of wool in one location, their superior market knowledge, and their desire for objective measurements have contributed to the deterioration of traditional producer marketing (NRC, 2008).

Some producers may have difficulty marketing their clip because they produce smaller clip sizes, such as those with less than a bag of wool or reside in areas with less wool production and fewer WW (NRC, 2008). In these cases, the shearers may act as the order buyers, purchasing wool clips directly from producers and accumulating large amounts of wool throughout the shearing season before selling the wool to a warehouse or CO-OP (Lupton, 2015). One example of a large buyer of wool from shearers is Groenewold Fur and Wool Company, which focuses on purchasing large quantities of high YLD rather than wool with low FD. Wool producers with smaller clips that do not otherwise market their wool to shearers, or the hand spinning industry commonly market their clips via cooperative marketing systems (CMS) to pool their wool with others to market it more efficiently.

Wool Pools and Cooperatives

Cooperative marketing systems allow smaller producers to sell wool based on GFW through two main methods, WP and fiber CO-OPs (Lupton, 2015). Cooperative marketing systems provide producers with a unique opportunity to sell their wool clips in locations where they may not have many options. As an added advantage, these systems allow buyers to purchase large quantities of wool at once, reducing sales cost and, in some cases, providing them with a graded uniform product (Lupton, 2015). Most CMS follow the same principles as producer marketing, but they are typically on a larger scale and have more wool growers involved. Cooperative marketing systems give producers the option of marketing greasy wool through two main distribution methods, fiber CO-OPs and WP.

Fiber CO-OPs are one variation of CMS for producers and may be established in similar areas as WP to add value to producers' wool where there is insufficient product to attract a commercial WW or buyer (NRC, 2008). After being delivered to the CO-OP central warehouse, the wool is classed by grade and type in an effort to ensure that every lot meets the potential buyer's specifications. Then, several similar wool groups from several growers are pooled to gain enough volume and style variation to attract buyers (NRC, 2008). In some cases, fiber CO-OPs may assist producers with wool preparation, packaging, and the use of objective measurements both for marketing and genetic selection purposes. Generally, fiber CO-OPs provide wool producers with a marketing channel for their wool, as well as packing and assembly services for wool buyers. Wool CO-OPs may even be effective in major wool-producing areas to enhance wool quality and provide producers with an additional marketing channel (NRC, 2008).

Wool pools are a CMS variation including groups of producers living in a common region (NRC, 2008). The WP will collect and consolidate different members' wool and then sell the resulting lots in bulk to warehouses, wool buyers, or mill agents (Lupton, 2015). A committee of producers, or board of directors, usually appointed by the membership, runs the WP. During the sale and delivery process, the board of directors may designate a sales committee to decide how best to sell the pool while also representing the growers (Lupton, 2015). In some situations, the board of directors may find it economical for members to grade and sort the wool before offering lots for sale at designated warehouses or shipping points (NRC, 2008; Lupton, 2015). The more progressive WP may even scour wool lots or take objective measurements to make lots more financially attractive to wool buyers. Nevertheless, the main drawback of the WP is that price differentials between high-quality clips and low-quality clips can be minimal (Lupton, 2015). If higher quality wool clips are not properly rewarded producers can lose their economic incentive to continue practices that improve the quality of their wool, resulting in an eventual decrease in the average quality of the entire WP. Therefore, the board of directors of the WP must ensure that producers are incentivized to produce higher-quality wool (Lupton, 2015). Since most of the wool from various WP systems are marketed domestically, it has become increasingly important for WP memberships to build a reputation for high-quality wool and commitment to continuous improvement (Lupton, 2015). It becomes even more relevant when considering that shrinking wool production has caused many WP to consolidate across larger geographical areas to retain the previous wool quantities, while others have been forced to disperse.

Like producer marketing systems, WP may sell wool lots to various buyers. Direct sales to wool mills happen, but in many cases, it is more effective for producers and WP systems to sell or consign wool to secondary marketers such as wool buyers or WW (Lupton, 2015). In fact, the majority of wool in the U.S. passes through a WW at some point during the marketing process.

Wool Warehouses

Wool warehouse systems offer producers various marketing and consignment options in various parts of the country, though they are typically located in regions where large quantities of wool are produced (Lupton, 2015). Similarly, the size of the WW depends on the level of wool production and the number of competing marketing operations in the area.

There are four stages in which WW will purchase during the marketing process: 1) before wool harvest, 2) straight off farm following shearing, 3) upon delivery of wool to the WW, or 4) after the producer has consigned (Lupton, 2015). The type and volume of wool purchased at a respective marketing stage are strongly influenced by the expected market conditions, as these project processor needs. Marketers should be aware of market projections to ensure wool purchasing decisions are informed and appeal to processors (Lupton, 2015). Wool warehouse owners must also act as agents for the producers during wool sales as producers typically trust WW owners to get the best price for their wool, unless they have a previously agreed-upon minimum bid (NRC, 2008).

There are three main selling methods utilized by WW and other marketing agents, including: private treaty (PT), sealed bid (SB), or auction-based (AU) sales (Lupton, 2015).

Depending on the number of buyers and the level of competition in the area, the method may differ. The quantity and quality of wool and market conditions at the time of sale may further influence the type of sales method used.

Sales Methods

Despite the advantages and challenges of each sales method, marketing agents typically have a preferred method (Lupton, 2015). Preferences for sales method are usually due to several contingencies, including market conditions or buyer presence.

Private treaty

Some wool is sold in major wool-producing states through PT, a sale that takes place with a single buyer and marketing agent, usually the woolgrower (Lupton, 2015). As the competition between buyers is limited, the agents selling wool through PT must have a thorough understanding of each wool lot's value to earn a fair price. Private treaty was once a popular selling method for many wool producers, but it has declined due to the increased use of objective measurements, buyer knowledge of wool market conditions, and buyer interest in centrally located large wool lots (NRC, 2008). These factors have increased the likelihood of PT wool being sold at lower prices than other methods, such as AU or SB.

Sealed bid

Sealed bidding is a popular method of selling among WP with large volumes of wool (Lupton, 2015). With this method, several buying agents are sent a memo asking for bids on the same lot of wool. The memo should contain sufficient information about the wool lots for sale, such as objective measurement information and lot weight, terms of sale, delivery and inspection dates, date of wool sale, and time of bidding (Lupton, 2015). Typically, each buyer is allowed a single bid and the bids of other buyers are unknown. The SB method may be more popular with

WP, but it is also effective for individual producers with clips large enough to fill a train car or truck (Lupton, 2015). The credibility of the marketing agent is one of the most important factors in the success of SB sales, especially in retaining return buyers. As part of maintaining their reputation, marketing agents should never refuse bids at fair market value and adhere to the terms of the bid solicitation letter (Lupton, 2015).

Auction-based

Wool AU sales are similar to SB sales in that both methods involve multiple buyers with an equal opportunity to bid; however, the AU method lets buyers publicly bid multiple times during the bidding period. During the auction, sale lots will be offered one at a time, with bidding occurring between buyers until the highest bidder is found (Lupton, 2015). In most AU sales, there will be a minimum bid value set on lots of wool to maintain a profit, even when some buyers lack interest. While AU sales are prevalent worldwide, particularly in Australia, they are not widely used in the U.S., who instead favors SB and PT methods (Lupton, 2011).

Role of wool buyers

The U.S. wool industry relies heavily on wool buyers as they market most domestic wool supply either directly into processing or exports (Brester, 2018). Most U.S. wool buyers are even considered the primary point of contact utilizing international exports for U.S. wool processors. As a result, wool buyers are familiar with the various specifications across wool processors and are not interested in buying lots of wool that do not meet those standards (Lupton, 2015). Therefore, to determine the quality of wool available, buyers require core testing information on each sale lot (NRC, 2008). With more U.S. wool purchased for exports each year, the international standards for wool quality become increasingly important to domestic market values.

In the U.S., fine wool production can better meet international wool standards and become more competitive in the global marketplace if genetic improvements are made to enhance production efficiency and quality. Originally, Borg (2004) utilized Targhee data to create the Western range index (WRI), which was the first index developed under the National Sheep Improvement Program (NSIP) to include wool production parameters. The WRI includes the estimated breeding values (EBV) of FW and FD, but they are given insufficient emphasis because the WRI is heavily driven by growth and ewe prolificacy. Further, wool EBV such as SL, FDCV, and CURV are vital aspects of wool quality that have not yet been included in index selection. Domestic wool production and quality can be improved by implementing a genetic selection program that further emphasizes fine wool production and quality traits.

Genetic improvement of the United States fine wool industry

The first step in developing any genetic selection program is to define a set of breeding objectives (Pearson, 1982). To provide the best genetic basis for increasing profitability, the breeding objective should include all traits associated with profitability. Once the profitable traits are determined, it is also necessary to understand the genetic parameters among the traits, given that index selection enables the simultaneous improvement of multiple traits (Hazel, 1943).

Genetic parameters of individual traits

Effective selection programs rely on accurate estimates of genetic parameters to anticipate the selection response and assess animals based on their potential contribution to breeding programs (Atkins, 1997). The genetic parameters include the heritability, as well as genotypic and phenotypic correlations. The heritability represents how much observed variation in a trait can be accounted for by genetic effects, thus determining to what extent a trait may respond to genetic selection (Hazel and Lush, 1942; Oldenbroek and van der Waaij, 2015). Both phenotypic and genotypic correlations between traits are also necessary, as they provide estimates of the relationship between two traits and the effect strength that selection on one trait may have on the other. These parameters are particularly important in index selection, a concurrent multi-trait selection program, because the simultaneous equations needed require accurate estimates of genetic parameters and either the SD or phenotypic variance of traits (Mrode, 2014). In some cases, it may be economical to utilize indirect selection and select an easily recognized, minor trait that can be readily measured rather than an economically significant trait that is difficult or expensive to quantify (Terrill and Hazel, 1945; James, 1982a). When heritability for the desired trait is moderate to high and genotypic and phenotypic correlations are high, there is a reasonable expectation that selection for the improvement of the less relevant trait will lead to similar gains for the significant trait. This methodology has been used in wool production as both SL and GFW can predict CFW (Terrill and Hazel, 1945). For indirect selection to work properly, genotypic, and phenotypic parameters must be accurate (Safari et al., 2005).

Parameter accuracy requires access to sizeable data sets that transcend generations, which are not always available for each relevant population. Numerous studies have estimated genetic parameters for most wool production traits among various fine wool sheep breeds; however, their estimates were varied due to differences in genetic makeup, breed type, age, sex, and production stage. Therefore, a thorough understanding of parameter estimates was acquired for FD, SL, FW, YLD, FDCV, and body weight (BW) traits by pooling estimates from literature sources covering a representative sample of the population rather than just a single group.

Heritability

Tables 1.2, 1.3, and 1.4 outline published heritability estimates of wool production and quality traits, as well as BW traits within scientific literature. Wool production traits evaluated were GFW, CFW, SL, FD, FDCV, CURV, and YLD. Body weight traits included in this review were birth weight, weaning weight (WWT), and yearling weight (YWT). A majority of the wool and BW trait estimates observed a moderate (0.20-0.40) to high (>0.40) heritability with a few notable estimates in Nagy et al. (1999) and Valera et al. (2009).

Heritability estimates for wool production traits GFW, CFW, and SL are reported in Table 1.2. Grease fleece weight heritabilities ranged from 0.58 ± unpublished SE (Ponzoni, 1995) to 0.12 ± 0.02 (Nagy et al., 1999). Safari et al. (2005) also published a weighted average heritability estimate of 0.37 ± 0.02 for GFW based on 20 Merino-based literature estimates. Clean fleece weight heritabilities ranged from 0.20 ± 0.11 (Rose and Pepper, 1999) to 0.59 ± unpublished SE (Ponzoni et al., 1995), and Safari et al. (2005) reported a weighted average heritability estimate of 0.36 ± 0.02 based on 30 literature estimates in Merino sheep. Heritability estimates for SL ranged from 0.17 ± 0.01 (Nagy et al., 1999) all the way to 0.75 ± 0.26 (Cloete et al., 2003), with a weighted average estimate of 0.46 ± 0.04 calculated using 15 literature estimates by Safari et al. (2005). For the most part, the heritabilities of GFW, CFW, and SL observed in literature were moderate to high, indicated that they will respond readily to selection. The range of heritability estimates suggest that there may be large differences in the genetic composition of these populations or breeds which will change the genetic variance. Differences in the genetic variance may be caused by variation in the allele frequency of the population and the linkage among loci. The low estimates of heritability reported by Nagy et al. (1999) for GFW and SL were likely due to the model used, as the flock by year effect was considered random, meaning that more of the variance was accounted in the heritability calculation.

Literature estimates of the heritabilities for wool quality traits FD, FDCV, CURV, and YLD are provided in Table 1.3. Fiber diameter heritabilities evaluated ranged from 0.08 ± 0.05 (Valera et al., 2009) to 0.76 ± 0.02 (Cloete et al., 2003). In addition, Borg et al. (2007) estimated a heritability of 0.57 ± unpublished SE through a simulation model of 5,000 Targhee ewes. The heritabilities of FDCV ranged from 0.23 ± 0.09 (Lee et al., 2002) to 0.74 ± 0.02 (Cloete et al., 2003) with a weighted average estimate of 0.52 ± 0.04 calculated using 14 literature estimates by Safari et al. (2005). Curvature heritabilities from the literature ranged from 0.39 ± 0.04 and 0.07 (Mortimer et al., 2017; Taylor et al., 1999, respectively) to 0.47 ± 0.02 and 0.15 (Huisman et al., 2008; Brown et al., 2002a, respectively). Heritabilities of YLD ranged from 0.34 ± 0.02 (Sherlock et al., 2003) to 0.72 ± unpublished SE (Ponzoni et al., 1995) with a weighted average heritability of 0.56 ± 0.03 calculated in Safari et al. (2005). Like wool production traits, the majority of the heritabilities reported for FD, FDCV, CURV, and YLD suggest that there should be a moderate to high response to selection. In addition to differences in the genetic variance between populations, the wide range of heritability estimates may also result from different environmental conditions under which the sheep were raised. For instance, if a sheep population had access to more abundant nutritional resources, the FD might be coarser than a population of similar genetic makeup that had access to fewer nutritional resources.

Some of the heritability estimates for wool BW traits, birth weight, WWT, and YWT are reported in literature are reported in Table 1.3. The heritabilities of birth weight ranged from 0.18 ± 0.01 (Safari et al., 2007a) to 0.39 ± 0.07 (Huisman et al., 2008). Safari et al. (2005) also estimated a weighted average heritability of 0.21 ± 0.03 based on 8 Merino breed studies.

Weaning weight heritabilities ranged from 0.10 ± unpublished SE (Borg et al., 2007) to 0.72 ± 0.03 (Huisman et al., 2008). The range of heritabilities for YWT were 0.26 ± unpublished SE (Notter and Hough, 1997; Borg et al., 2007) to 0.51 ± 0.04 (Swan et al., 2008). The estimated heritability by Borg et al. (2007) was calculated through a simulation study of a 5,000 Targhee ewe base flock. Generally, the heritabilities for birth weight, WWT, and YWT indicate that selection will result in a low to moderate response to selection. However, there were a few high heritabilities estimated for WWT and YWT by Huisman et al. (2008) and YWT by Swan et al. (2008). The BW heritabilities of Huisman et al. (2008) may have been inflated due to the lack of animal's dam information, which prevented the adequate division of direct and maternal variance and inflated the additive genetic variance. Additionally, the genetic and environmental variance may be a significant contributor to the differences between YWT heritability estimates, as the studies with different populations of Australian Merino sheep tended to be larger than those estimated using different populations of American Targhee sheep.

Overall, the scientific literature for wool and BW trait heritabilities suggest that for most wool traits there will be a moderate to strong response to selection, while BW traits will have a low to moderate response to selection. The variations between heritability estimates for different sheep populations and breeds suggest large variation in the genetic and environmental variances between populations and breeds. These differences of genetic and environmental variances are likely caused by the genetic diversity of each population, the variety of management practices that occur across the globe, and other genotypic by environmental effects. These factors may also influence the genetic and phenotypic correlations, as variant component estimates are used in the correlation calculation.

Genetic Correlation

Table 1.5 outlines literature estimates of genetic correlations among wool and BW traits. The wool traits reviewed were FD, SL, GFW, CFW, FDCV, CURV, and YLD. Body weight traits were birth weight, WWT, and YWT. A majority of the genetic correlations observed between wool and BW trait estimates had a low (0.00-0.20) to moderate (>0.20-0.60) magnitude and were favorable, with a few exceptions for correlations with FD, FW, and FDCV.

Fiber Diameter

For the most part, the genetic correlations between FD and other traits were weak to moderate in strength. The lowest genetic correlation observed was -0.01 ± 0.04 between FD and YLD (Swan et al., 2008). One strong correlation was found between SL and SC at -0.69 ± unpublished SE (Hanford et al., 2003), but the lack of a published SE means that the uncertainty of this estimate is unknown. Spin count was used as an alternative to evaluate the correlations between FW and FD. The difference in sign between FD and SL (+) and SC and SL (-) is due to the field of measurement used. For SC, finer fibered fleeces will have a higher value (e.g., 60s, 70s, 80s) on the scale compared to coarser fleeces (e.g., 50s and 40s), while within the micron system, finer fleeces will have a lower value (e.g., 19, 18, 17) and coarser fleeces will have a higher value (e.g., 25, 26, 27; Kott, 1993). The larger magnitude observed between SC and SL compared to FD and SL may be attributed to the SC being a measurement based on length, specifically the number of hanks of yarn that can be spun from 0.45 kg of clean wool. The influence of SL in this measurement logically indicates that the correlation estimates between SC and SL would be stronger than those of FD and SL.

Though a majority of genetic correlations with FD are weak to trivial, unfavorable correlations were found between FW measurements, SL, FDCV, YLD, WWT, and YWT with

FD. The unfavorable genetic correlations between fleece and body production traits with FD may be partially attributable to pleiotropic effects in which increased FD, SL, and FW are influenced by the same alleles as those that influence increased WWT and YWT. Nonetheless, this does not explain why genetic correlations between FD and birth weight, though weak, were negative and favorable. The genetic correlation between FD and birth weight could possibly be caused by linkage between genes that influence higher BW and lower FD within a population, in which the two alleles tend to be inherited together. Still, it is unlikely that genetic selection for decreased FD will result in significant changes in YLD, FDCV, CURV, SL, birth weight, and WWT over short selection periods. For this reason, the stronger unfavorable correlations, such as those between FW measurements and FD, are key concerns for breeders of fine wool because of the adverse relationship between FW measurements and FD. To add value to their operation, producers desire greater FW and finer FD; however, these changes will take time as these characteristics tend to work in opposition to one another.

Staple Length

The genetic correlations of SL were largely moderate with some weak estimates reported between GFW, FDCV, birth weight, WWT. The strongest genetic correlation reviewed was 0.56 ± unpublished between SL and GFW in Rambouillet sheep (Bromley et al., 2000), whereas the weakest correlation observed was 0.00 ± unpublished between SL and WWT in Targhee sheep (Borg et al., 2007). Though not the lowest estimate overall, genetic correlations between SL and FDCV were consistently weaker than other traits with correlations that ranged from -0.30 ± unpublished (Di et al., 2011) to 0.01 ± unpublished (Swan et al., 1995). The estimate reported in Di et al. (2011) was higher than the other estimates between SL and FDCV and may have been caused by the presence of linked genes controlling SL and FDCV or differences in the gene frequency of the population. In contrast, genetic correlation estimates between SL and GFW tended to be stronger than others, with the weakest correlation being 0.27 ± 0.02 estimated by Huisman and Brown (2009). Genetic correlations of SL with CFW were only slightly weaker with correlations between 0.21 ± 0.14 (Wuliji et al., 2001) and 0.44 ± unpublished (Purvis and Swan, 1997). Genetic correlations between FW measurements and SL were expected to be stronger since increased wool production logically leads to longer and heavier fleeces.

Similar to the FW traits, most of the genetic correlations of SL were favorable, except for FD and CURV. The favorable correlations of SL were expected as increased BW and surface area promote increased wool production volume through increased SL, and thus, increased YLD and FW measurements (Rogers and Schlink, 2010). Though there was a favorable correlation between SL and FDCV, literature estimates with a published SE values indicated that there would be little noticeable changes in FDCV as longer SL was selected. Unlike other traits evaluated the genetic correlations observed between SL and CURV were inconsistent with one estimate of -0.38 ± 0.05 (Huisman and Brown, 2009) and another of 0.26 ± 0.09-0.38 (Brown et al., 2002b). The SE range given by Brown et al. (2002b) indicates that the positive correlation may have a large amount of variability, though without a specific SE this cannot be known with certainty. The with variation between these estimates may be due to larger amounts of variation between the different genetic compositions of each population. Based on the relationship that occurs over time between CURV and FD and between FD and SL it is likely that CURV will decrease over time if longer SL is selected for. The favored direction of the genetic correlation between SL and CURV is also variable, as desired CURV is largely dependent on the end goal of the fiber (Cottle and Baxter, 2015).

Grease Fleece Weight

Genetic correlations between GFW and other wool traits tended to be weak, though high correlations were observed between GFW and CFW. Additionally, the few genetic correlations observed between GFW and CURV were inconsistent with one estimate of 0.44 ± 0.09-0.38 (Brown et al., 2002b) and another of -0.19 ± 0.01 (Huisman and Brown, 2009). The inconsistency of the genetic correlations between GFW and CURV suggests that there may be a difference in the allele frequencies of the population tested. Most of the genetic correlations between GFW and BW traits were moderate, with a few high and low estimates that occurred for GFW genetic correlations with birth weight and WWT. The highest genetic correlation observed was 0.90 ± unpublished and 0.01 between GFW and CFW (Swan et al., 1995, 2008). Strong correlations between GFW and CFW were expected because, as fleece production increases, fiber, suint, and lanolin weight also tend to increase. The genetic aspect indicated that the correlation between GFW and CFW might be influenced primarily by additive genetic effects, such as pleiotropy. In contrast, the weakest GFW genetic correlation reviewed was 0.06 ± 0.06 between GFW and FDCV (Swan et al., 2008). The genetic correlations between GFW with FDCV and YLD were consistently weaker than other correlations, with a high magnitude estimate of 0.19 ± 0.03 between GFW and FDCV. The weaker correlations between GFW with FDCV and YLD indicate that the selection of increased or decreased GFW may have to happen over a longer period of time before significant changes to FDCV and YLD occur.

Despite the low magnitude GFW genetic correlations with FDCV and YLD, the GFW genetic correlations with both traits were unfavorable, similar to FD, whereas the GFW genetic correlations with CFW, SL, birth weight, WWT, and YWT were all favorable. One exception was the genetic correlation of -0.08 ± unpublished between GFW and birth weight (Di et al., 2011), which was considerably different from the other estimates of the genetic correlations between GFW and birth weight. The deviation of the -0.08 ± unpublished (Di et al., 2011) genetic correlation between GFW and birth weight may have been caused by a linkage effect present in the Chinese Merino population studied. Nevertheless, as increased GFW, SL, YLD, and decreased FD and FDCV are favored within the wool industry, selection will have to occur over time based on the unfavorable GFW correlations with FD, FDCV, and YLD.

Clean Fleece Weight

A majority of the CFW genetic correlations with other wool and BW traits were weak to moderate, with strong correlations between CFW and GFW as described previously. Compared to GFW, the genetic correlation estimates between CFW and CURV were more consistent, with one estimate of -0.64 ± 0.08 (Taylor et al., 1999) and another of -0.25 ± 0.01 (Huisman and Brown, 2009). The range between these genetic correlations between CFW and CURV could partially be explained by a difference in the allele frequencies of each population evaluated, though further evaluation of the relationships of other wool traits with CURV is needed. The larger genetic correlation between CFW and CURV of -0.64 ± 0.08 (Taylor et al., 1999) was the strongest estimate reviewed, excluding the genetic correlations between CFW and GFW, whereas the lowest magnitude estimate was 0.00 ± 0.07 (Swan et al., 2008) between CFW and FDCV. The genetic correlations between CFW and FDCV were consistently weaker than other CFW correlations, with a high magnitude estimate of 0.19 ± 0.10 (Safari et al., 2005). Similarly, genetic correlations between CFW and birth weight were also lower compared to other relationships, with estimates between 0.10 ± 0.03 (Safari et al. 2007b) and 0.18 ± 0.18 (Wuliji et al., 2001). Genetic correlations of CFW with FDCV and birth weight, as well as uncertainty measures, indicated that correlations were near zero, which suggested that short-term selection for increased CFW would likely have little impact on FDCV and birth weight.

For the most part, the genetic correlations of CFW with other wool traits and BW measurements were favorable, apart from FD, FDCV, and CURV. The genetic correlations between CFW and CURV indicated that selection for increased CFW would lead to decrease CURV, which is likely connected to the fact that CURV generally increases with decreased FD, and FD is unfavorably correlated with CFW. These associations also suggested that there may be influences of pleiotropic gene effects on decreased CFW and increased CURV, or vice versa. The direction of the genetic correlation between CFW and CURV is not defined as favorable or unfavorable due to the fact the optimal CURV level is highly dependent on the processing system in which the wool is placed and end product attributes desired. For instance, higher CURV may be more desirable for knitwear production, whereas lower CURV may be desired to produced fine worsted products. In order to achieve a goal that involves both higher CURV and heavier CFW, selection will have to be conducted over a longer period of time than a goal with lower CURV and heavier CFW. Despite this, selection for increased CFW will tend to lead to strong improvements of GFW, moderate improvements of SL, YLD, WWT and YWT, and weak improvements over time in birth weight.

Yield

Fewer literature estimates of YLD genetic correlations were found compared to other wool and BW traits. Those reviewed tended to have weak to moderate correlations with other wool traits and weak correlations with BW traits. One exception was the genetic correlation between YLD and birth weight which had a moderate correlation of 0.25 ± 0.01 (Safari et al., 2005). As the correlations in Safari et al. (2005) were weighted average estimates from several other studies, reported in Safari et al. (2003), it is possible that the stronger estimate between YLD and birth weight could have been caused by populations with varied additive genetic effects. The strongest genetic correlation estimate reported was 0.38 ± 0.14 (Brash et al., 1997) between YLD and FDCV, whereas the weakest correlation observed was -0.00 ± 0.07 (Swan et al., 2008) between YLD and YWT. Like that of the genetic correlation of YLD and birth weight, the strong correlation between YLD and FDCV may suggest the presence of varied allele frequencies, linked genes or pleiotropy. In contrast, the genetic correlations between YLD and YWT are so weak that it is likely the selection of increased YLD will have negligible to no effects on YWT, with similar associations between YLD with FD and WWT.

Likely because many of the genetic correlations of YLD are weak to negligible, the direction of the YLD genetic correlations were varied. Generally, genetic correlations of YLD with CFW, SL, and FDCV were favorable, while genetic correlations of YLD with FD, GFW, and birth weight were unfavorable. The YLD correlations with WWT and YWT were mixed, with favorable and unfavorable correlation estimates. The inconsistency of the YLD genetic correlations with WWT and YWT may be due in part to the trivial strength of the estimates, as the SE values cause many of the estimate to cross or come close to zero.

Fiber Diameter Coefficient of Variation

The majority of genetic correlations of FDCV were weak to moderate and had a large amount of variation between FDCV genetic correlations of CURV and BW traits. The highest magnitude genetic correlation of FDCV was 0.87 ± 0.09-0.38 (Brown et al., 2002b) between FDCV and CURV. While this estimate may suggest a strong positive relationship based on additive genetic effects, it was inconsistent with the other genetic correlation of 0.01 ± 0.01 (Huisman and Brown, 2009) between FDCV and CURV. However, the strong genetic correlation in Brown et al. (2002b) may be inflated due to the very small dataset of just 501 records used in the evaluation, which affects the allele frequency of the population. The Huisman and Brown (2009) estimate of 0.01 ± 0.01 between FDCV and CURV was also the weakest genetic correlations of FDCV, excluding correlations of those traits included earlier. The range of genetic correlations signals the need for further estimation of the associations between FDCV and CURV. In the case of BW traits, FDCV genetic correlations with birth weight and YWT were moderate, each with a weak correlation of 0.16 ± 0.03 (Safari et al., 2007b) and -0.07 ± 0.04 (Huisman and Brown, 2008), respectively. In contrast, genetic correlations between FDCV and WWT were low with one weak correlation of -0.31 ± unpublished (Di et al., 2011). The weaker genetic correlations between FDCV and WWT compared to other BW traits may be caused by pleiotropic effects or the linkage of genes. Additionally, the variation of genetic correlations between FDCV with CURV and BW traits may partially be due differences in the allele frequencies of the populations evaluated.

Unlike the strength of the genetic correlations of FDCV, the direction of the correlations were more consistent. The genetic correlations between FDCV and CURV indicated that selection for decreased FDCV would also decrease the CURV. This relationship was expected as increased FDCV and CURV occur with the selection of finer fibers. Except for birth weight, which was unfavorable, the genetic correlations of FDCV with WWT and YWT were negative and favorable. Since increased WWT and YWT may also increase FW measurements and FD, favorable correlations with FDCV were expected. Still, selection for decreased FD and FDCV will occur over a longer period of time due to the unfavorable correlations compared to selection for increased YWT and decreased FDCV.

Curvature

In comparison to other traits, very few genetic correlations of CURV were found between BW traits. Those found indicated weak genetic correlations of -0.05 ± 0.16, 0.13 ± 0.06, and -0.04 ± 0.05 between CURV and birth weight, WWT, and YWT, respectively (Huisman and Brown, 2008). The high relative SE values of these estimates suggest that there is a high level of uncertainty of these estimates, which may indicate that selection for increased CURV will have negligible effects on BW measurements. Nevertheless, further estimation of genetic correlations between CURV and BW measurements are needed, as the Huisman and Brown (2008) measurements may be impacted by the allele frequency or linkage effects within the population.

Despite the weak strength, the genetic correlations between CURV and BW traits indicated that selection for decreased CURV would lead to increases in birth weight and YWT, whereas increased CURV would lead to increased WWT. The direction of the genetic correlation between CURV and WWT were inconsistent with other trait relationships, as increased CURV typically indicates decreased FD which is unfavorably correlated with WWT. This genetic correlation could possibly be caused by linked genes that influence increased CURV and WWT.

Overall, the majority of genetic correlations for wool and BW traits reviewed were weak to moderate in strength. The variation of the genetic correlations between populations are primarily due to differences in the genetic variance, which is commonly caused by variations in the allele frequency, linkage disequilibrium among loci, and pleiotropy (Falconer and Mackay, 1996). Allele frequency significantly affects genetic correlation estimates as different populations have different proportions of homozygous and heterozygous alleles. Linkage disequilibrium occurs when there is an allelic association at two or more loci, and the closer they are, the less likely they are to be split by recombination. There appears to be a correlation between the traits associated with the linked loci, and the closer the loci are to each other, the stronger the correlation. Regardless, correlations due to linkage decrease over generations and are affected by the allele type present at each locus. Pleiotropy occurs when a gene or a set of genes controls multiple traits, which can cause significant genetic correlations (Falconer and Mackay, 1996). These factors cause variation of the genetic correlations, which is one aspect of the phenotypic correlation.

Phenotypic correlation

Table 1.5 outlines literature estimates of phenotypic correlations among wool and BW traits. Similar to the genetic correlations, the wool traits reviewed were GFW, CFW, SL, FD, FDCV, CURV, and YLD. Body weight traits were birth weight, WWT, and YWT. A majority of the phenotypic correlations observed between wool and BW trait estimates were lower than the genetic correlations with strengths that ranged from low (0.00-0.20) to moderate (>0.20-0.60).

Fiber Diameter

The phenotypic correlations of FD were mostly moderate to low in strength and followed the same direction as the genetic correlations, though they tended to be lower values (Table 1.5). The strongest phenotypic correlation of FD observed in this review was -0.33 ± 0.02-0.06 between FD and FDCV (Brown et al., 2002b). This correlation was significantly higher than the genetic correlation of -0.02 ± 0.09-0.38, suggesting that there may be some environmental or non-additive genetic effects influencing both FD and FDCV. Huisman and Brown (2009) also supported the presence of an environmental component between FD and FDCV with a phenotypic correlation of -0.31 ± 0.03, which was significantly higher compared to the genetic correlation. Other phenotypic correlations of FD that may be influenced partially through environmental or non-additive genetic components are 0.29 ± 0.01 (Swan et al., 2008) between

FD and GFW, 0.22 ± 0.02 (Swan et al., 2008) between FD and CFW, 0.29 ± 0.05 (Huisman and Brown, 2009) between FD and SL, 0.08 ± unpublished (Di et al., 2011) and 0.07 ± 0.01 (Safari et al. 2007b) between FD and WWT, and 0.20 ± 0.05 (Swan et al., 2008) between FD and YWT.

In some cases, the phenotypic correlations are much lower than the genetic correlations. This type of relationship may also indicate a significant environmental correlation between traits with an opposite direction from the genetic and phenotypic correlations. Phenotypic correlations that were much lower than the estimated genetic correlations were 0.10 ± unpublished (Borg et al., 2007) between FD and GFW, and 0.12 ± 0.03 (Lee et al., 2002), 0.15 ± 0.03 (Brash et al., 1997), and 0.26 ± 0.01 (Huisman and Brown, 2009) between FD and CFW. Though some phenotypic correlations for FD were divergent from the genetic correlations, many were similar, indicating there may be less of an environmental or non-additive component in some populations.

The lowest phenotypic correlations of FD were 0.00 ± 0.01 and 0.02 (Safari et al., 2007b; Swan et al., 2008, respectively) between FD and YLD, and were similar to the genetic correlations. This was anticipated, as the weak genetic and phenotypic correlations between FD and YLD indicate that there is little to no relationship between the traits as the correlation values and SE are so close to zero. Many of the phenotypic correlations between FD and BW measurements were also similar to the genetic correlations, which indicated that the variance of estimates may be explained more through additive genetic affects with less emphasis on environmental and non-additive components. This relationship was unexpected, as correlation estimates between FD and BW traits may be partially attributed to an elevated level of cell proliferation which generates increased BW, FW, SL, and thickness of fibers, which may indicate an environmental component (Rogers and Schlink, 2010). In the case of birth weight, the weak but numerically favorable correlation with FD may partially be caused by increased nutrition to the lamb around the time of birth (Kelly et al., 1996). Logically, the increased nutrition to the lamb subsequently increases the birth weight and initiates secondary follicle development that tends to produce finer fibers, which would indicate a correlation between BW and uterine environment. After one month of age, instead of increasing follicle initiation and fiber development, increased nutrition of the sheep is more likely to result in heavier BW, heavier GFW, and longer SL, which is consistent with the direction of the correlations between WWT and YWT with FD (Lupton, 2015). Ultimately, the similar genetic and phenotypic correlations suggest that there may be a combination of environmental, non-additive genetic effects and additive genetic components such as pleiotropy or allele frequency differences between populations.

Staple Length

Phenotypic correlations for SL were moderate to weak, with primarily moderate SL correlations between FW measurements and CURV and low SL correlations between FDCV and BW traits. The SL phenotypic correlations with FD and YLD had both moderate to weak estimates. The highest phenotypic correlation estimated was 0.52 ± 0.05 between SL and CFW and was significantly higher than the genetic correlation of 0.37 ± 0.01 (Huisman and Brown, 2009), indicating what appears to be an increased environmental component within the representative population. Within the Merino population evaluated in Huisman and Brown (2009), the presence of an increased environmental component between SL and FW measurements was further supported by a phenotypic correlation of 0.42 ± 0.06 between SL and GFW that was higher than the genetic correlation of 0.27 ± 0.02. The environmental component between SL and FW measurements likely occurs because wool production increases with changes in environmental conditions, such as improved nutrition or overall health, which therefore increases SL and FW measurements. Additionally, the records evaluated in Huisman and Brown (2009) were obtained from Australian and New Zealand Merino ram flocks, which were likely reared in very different environments and may have caused an increase in the phenotypic correlations.

In contrast, the lowest phenotypic correlation was 0.05 ± unpublished between SL and birth weight and was much lower than the genetic correlation of 0.50 ± unpublished (Di et al., 2011). The large difference between the genetic and phenotypic correlations evaluated indicate that there may be a larger environmental correlation than those above due to the larger diversion between the genetic and phenotypic correlations. Similar relationships between phenotypic and genetic correlations were observed in other BW measurements, GFW, CURV and FDCV, specifically 0.20 ± unpublished (Di et al., 2011) and 0.10 ± 0.02 (Swan et al., 2008) between SL and WWT, 0.20 ± unpublished (Di et al., 2011) between SL and YWT, 0.32 ± 0.08 (Safari et al., 2005) between SL and GFW, -0.25 ± 0.01 (Huisman and Brown, 2009) between SL and CURV, and -0.07 ± unpublished between SL and FDCV (Di et al., 2011). Di et al. (2011) tended to have much lower phenotypic than genetic correlations, which may be explained, at least in part, by differences in management practices between flocks raised in the same region but with different managers.

While some of the SL phenotypic correlations were significantly different from the associated genetic correlations, many were similar to the genetic correlations suggesting that the additive genetic effects were more prominent. Similar phenotypic and genetic SL correlations were present for FD, GFW, CFW, FDCV, YLD, and YWT. Like the FD phenotypic correlations, the SL phenotypic correlations that were similar to genetic correlations may indicate a combination of environmental, non-additive genetic effects, and additive genetic effects. Though, the environmental component will likely be lower than those with divergent correlations.

Grease Fleece Weight

The phenotypic correlations for GFW were a combination of weak to moderate strengths, with an exception of strong correlations between GFW and CFW. Phenotypic correlations of GFW with FDCV and YLD were mostly weak, while GFW correlations with CURV, WWT, and YWT were generally moderate. The phenotypic correlations between GFW and birth weight were divided between weak to moderate estimates. The highest phenotypic correlation of GFW was 0.94 ± unpublished between GFW and CFW and was similar to the genetic correlation of 0.90 ± unpublished (Swan et al., 1995). Similar phenotypic estimates were observed between GFW and CFW with a low magnitude estimate of 0.79 ± 0.01 (Rose and Pepper, 1999). The phenotypic and genetic correlation estimates between GFW and CFW are so close to unity meaning that they are close to being the same trait, this was not surprising as GFW is a measure of the CFW with the addition of non-wool aspects such as dirt, lanolin, and suint. Despite the similarity between estimates, the phenotypic correlations between GFW and CFW are so strong that there is likely a significant environmental correlation between the traits which could be caused by the influence of nutrition, health, or management practices on wool growth. Though a majority of the phenotypic correlations of GFW were similar to the genetic correlations, they were likely not strong enough to incur a significant environmental or non-additive genetic component similar to the correlations between GFW and CFW.

In many cases, the GFW phenotypic correlations were much higher than the genetic correlations. The strongest estimate with this type of relationship was 0.79 ± 0.01 between GFW and CFW with a genetic correlation of 0.65 ± 0.11 (Rose and Pepper, 1999), which supports the presence of a significant environmental correlation between GFW and CFW. Other phenotypic correlations that were much higher in magnitude than the genetic correlations were 0.36 ± 0.10 (Safari et al., 2005) between GFW and FDCV, -0.37 ± 0.05 (Huisman and Brown, 2009) between GFW and CURV, 0.34 ± 0.03 (Wuliji et al., 2001) between GFW and birth weight, 0.49 ± 0.02 (Swan et al., 2008) and 0.48 ± 0.02 (Wuliji et al., 2001) between GFW and WWT, and 0.46 ± 0.02 (Swan et al., 2008) and 0.44 ± unpublished (Safari et al. 2007b) between GFW and YWT. The diversion of these phenotypic correlations from genetic correlations indicates the presence of an environmental or non-additive genetic component between the traits.

Similar environmental or non-additive genetic components were predicted when the phenotypic correlations were much lower in magnitude than the genetic correlations, though these occurred less often for GFW phenotypic correlations. Weaker phenotypic than genetic correlations that occurred were 0.01 ± 0.01 (Huisman and Brown, 2009) between GFW and FDCV, -0.07 ± 0.01 (Safari et al., 2007b) and 0.04 ± 0.02 (Swan et al., 2008) between GFW and YLD, and 0.28 ± unpublished (Di et al., 2011) between GFW and WWT. The proposed environmental component and variation of the phenotypic correlations within these GFW correlations may be due to variations in the region the animals were raised in, the nutritional levels achieved, or different management practices between flocks within and between populations tested.

Clean Fleece Weight

The phenotypic correlations of CFW with wool and BW traits tended to be slightly higher in magnitude than the genetic correlations. The majority were moderate, with the exception of the strong phenotypic correlations between CFW and GFW and low correlations between CFW and FDCV. In addition, one weak phenotypic correlation of 0.20 ± unpublished (Safari et al., 2007b) was reported between CFW and birth weight. Excluding the correlations between CFW and GFW, the strongest CFW phenotypic correlation estimated was -0.51 ± 0.04 (Huisman and Brown, 2009) between CFW and CURV. This correlation was much higher than the associated genetic correlation of -0.25 ± 0.01, which suggests the presence of an environmental component among the relationship between CFW and CURV. Other phenotypic correlations of CFW that were stronger than the genetic correlations and may be influenced by environmental or non-additive genetic components were -0.12 ± 0.02 (Swan et al., 2008) between CFW and FDCV, 0.34 ± 0.03 (Wuliji et al., 2001) and 0.24 ± 0.10 (Safari et al., 2005) between CFW and birth weight, and 0.32 ± unpublished (Safari et al., 2007b) and 0.47 ± 0.02 (Wuliji et al., 2001) between CFW and WWT. Several of the divergent correlations for both types of FW were observed in Wuliji et al. (2001) suggesting there may be a significant environmental effect for the population evaluated. Possible environmental components may occur as a result of different management or feeding practices between the 12 ram-breeding flocks that were used in Wuliji et al. (2001).

In some situations, the phenotypic correlations of CFW were much lower than the genetic correlations, which also indicate the presence of an environmental or non-additive genetic component between traits. Unlike GFW, only three phenotypic correlation estimates were much lower than the genetic correlations, -0.04 ± 0.09 (Safari et al, 2005) and -0.05 ± 0.01 (Huisman and Brown, 2009) between CFW and FDCV, and -0.31 ± 0.01-0.03 (Taylor et al., 1999) between CFW and CURV. This type of relationship between the genetic and phenotypic correlations may indicate a significant environmental correlation between traits that is an opposite direction from the genetic and phenotypic correlations.

In contrast, the majority of the phenotypic correlations with CFW were similar to the genetic correlations. The lowest phenotypic correlation observed for CFW was 0.01 ± 0.01 between CFW and FDCV and was similar to the genetic correlation of 0.01 ± 0.02 (Safari et al., 2007b). Though the other estimates of CFW and FDCV may suggest a slight environmental correlation, the weak genetic and phenotypic correlations between CFW and FDCV indicate only a trivial relationship between the traits as the correlation values and SE are so close to zero. The phenotypic correlations of CFW with YLD and YWT were all similar to the associated genetic correlations, which indicated that more of the variance of estimates may be explained through additive genetic effects rather than environmental or non-additive genetic effects.

Yield

The phenotypic correlations of YLD with other wool and BW traits had a weak strength, apart from moderate correlations with SL, CFW, and an estimate of -0.38 ± 0.02 (Hatcher and Atkins, 2000) between YLD and CURV. The lowest phenotypic correlation of YLD was 0.00 ± 0.02 between YLD and WWT and was similar to the associated genetic correlation of -0.07 ± 0.10 (Safari et al., 2005). The inconsequential phenotypic correlations of YLD with WWT and YWT support the similar observations of the genetic correlations and suggest that the association of YLD with WWT and YWT is trivial.

Despite most of the phenotypic correlations being similar to the genetic correlations, a few phenotypic correlations reported were much weaker than the genetic correlations. The weaker phenotypic correlations were -0.03 ± 0.03 (Brash et al., 1997) between YLD and FDCV and 0.05 ± 0.02 (Safari et al., 2005) between YLD and birth weight. The divergence of the phenotypic correlations from the genetic correlations indicates the presence of an environmental or non-additive genetic component. For Safari et al. (2005) it is likely that the studies used to calculate the weighted estimate of 0.05 ± 0.02 had a wide range of management practices and environments, which may have led to an environmental correlation of increased magnitude.

Fiber Diameter Coefficient of Variation

Generally, the phenotypic correlations of FDCV were lower and more consistent than the associated genetic correlations. Excluding those already discussed, only one moderate phenotypic correlation of -0.21 ± 0.01 was observed between FDCV and YWT, which was also much lower than the associated genetic correlation of -0.37 ± 0.06 (Safari et al., 2007b). This relationship between the phenotypic and genetic correlation of FDCV and YWT was supported by an estimate of -0.01 ± unpublished (Di et al., 2011). The much lower phenotypic correlations between FDCV and YWT indicates the presence of an environmental correlation that is the opposite direction of the genetic and phenotypic correlations. Similarly, the phenotypic correlations between FDCV and birth weight were all much lower than the genetic correlations suggesting that environmental or non-additive genetic components tend to have a larger impact on the relationship. Other phenotypic correlations that were much lower than the genetic correlations were 0.04 ± 0.02-0.06 (Brown et al., 2002b) between FDCV and CURV and -0.04 ± unpublished (Di et al., 2011) between FDCV and WWT.

In some cases, the phenotypic correlations were similar to the genetic correlations. One of the weakest phenotypic correlations of FDCV was 0.01 ± 0.04 between FDCV and CURV and was similar to the genetic correlation of 0.01 ± 0.01(Huisman and Brown, 2009). This relationship indicates a weaker environmental correlation as more emphasis comes from additive genetic factors. Similar relationships between the phenotypic and genetic correlations of FDCV were -0.15 ± 0.02 (Swan et al., 2008), -0.10 ± 0.01 (Safari et al., 2007b), and -0.08 ± 0.02 (Huisman and Brown, 2008) between FDCV and WWT, and -0.20 ± 0.01 (Swan et al., 2008) and

-0.08 ± 0.02 (Huisman and Brown, 2008) between FDCV and YWT. While these relationships occur, the lower correlations of FDCV still indicate that significant changes in wool and BW traits will occur over a longer period of time compared to those traits with stronger correlations.

Curvature

Similar to the genetic correlations, there were very few phenotypic correlations observed between CURV and BW traits. Of those reviewed, there was a high magnitude correlation of 0.18 ± unpublished (Roldan et al., 2010) between CURV and birth weight, and a low magnitude phenotypic correlation of -0.01 ± 0.01 (Huisman and Brown, 2008) between CURV and YWT. Most estimates were similar but still lower than the genetic correlations, with one estimate of 0.04 ± 0.02 between CURV and WWT that was much lower than the genetic correlation of 0.13 ± 0.06 (Huisman and Brown, 2008). This relationship may indicate the presence of a slight environmental component between CURV and WWT. Though, the weak phenotypic correlations between CURV and BW traits propose a negligible relationship between the traits like the genetic correlations.

In summary, the phenotypic correlations of wool and BW traits were weak to moderate in strength and were typically similar to the genetic correlations. Variation between the phenotypic correlations between populations are primarily due to the genetic and environmental correlations. Environmental influences on the phenotypic correlations can occur through variations of nutrition, management practices, and general health of the population. For instance, ewes that are fed above their maintenance level will tend to have coarser wool than those fed at or below maintenance. The accurate estimation and knowledge of phenotypic correlations may be used to advance selection through tools like selection indices.

Conclusion

When creating a selection index, knowledge of the genetic parameters of traits is crucial for calculating the simultaneous equations required and understanding the effect that selection on one trait will have on another. Heritabilities and genetic correlation estimates provide an idea of how genetic selection will impact a trait, and its correlated traits, whereas phenotypic correlations give an insight into the extent that environmental or non-additive genetic effects will influence the correlation between two traits (Searle, 1961). Due to the large amount of data and computation required to attain accurate genetic parameter estimates, economic selection indices commonly incorporate only traits accounting for a significant portion (e.g., 10%) of profit into the breeding objective (Pearson, 1982). In a strictly economic selection index, economic estimates of the traits guide the amount of emphasis that should be placed on each trait that has an impact profitability (MacNeil et al., 1997). Thus, in order to develop an accurate selection program and assess the profitability potential of each trait, relative economic value (REV) for the traits need to be accurately assigned (Hazel, 1943).

Establishing economically relevant traits

Relative economic value is defined by Hazel (1943) as the expected monetary gain of a one-unit enhancement in a trait, given that all other traits in the aggregate genotype (the breeding objective weighted by economic value of each trait) remain constant. For instance, for every micron increase in FD, the expected monetary gain is reduced by a certain amount given that all other traits are constant, which would produce a negative economic value. In some cases, the REV can also be presented as the monetary gain of a one SD increase in a trait. Relative economic values for index usage can be projected using historical price averages, production expense figures, and discounts in production growth costs (Hazel, 1943). It is complex to calculate REV estimations because economic values may differ by breed, region, and even by year due to shifts in demand. Another layer of complexity is applied when considering that REV should be designed based on present and future production systems, as significant genetic change can only occur across multiple generations (Amer, 1999). Though these considerations make estimating REV challenging, scientists need to try and develop economic weights that are as accurate as possible. An error associated with the creation of any aspect of an index may result in a loss of genetic gain and efficiency compared to the perfect index, as traits may be over or underemphasized (Vandepitte and Hazel, 1977). Due to the complexity and importance of estimating economic values, there have been many studies that discuss the most effective method of calculating REV (James, 1982b; Brascamp et al., 1985; Groen, 1989; Nielsen & Amer, 2007; and Just et al., 2018). The methods available can generally be divided into objective and non-objective methodologies (Groen et al., 1997; Just et al., 2018).

Theory of establishing economic values

Objective methods are a commonly used method of deriving REV, as they are purely economic in nature, and typically remove producer bias which may not always promote profitability (Just et al., 2018). Typically, equations are used to model production system behavior for different breeding systems, environments, and management programs. These objective methods can be divided further into positive (data evaluation), and normative (data stimulation) approaches. In contrast, non-objective approaches to deriving REV are formulated based on a desired-gains approach or subjective methods directly through the choices made by producers. While non-objective approaches cannot be used to develop economic selection indexes, they are a more straightforward approach that enables producers to develop clear breeding objectives without statistical computation (Gizaw et al., 2018). Non-objective methodology may be used to introduce producers to the concept of economic indexes using simplified approaches.

Non-Objective

The desired gains approach is used to develop a REV when a set amount of genetic gain is required for a trait (Groen, 1989). Shultz (1986) provided an example of the acceptability of this method used in the poultry industry, which is ideal because of the significant trait relationships that tend to move in a stairstep pattern rather than linearly, and the REV were based on product performance compared with other producers. The desired gains method gives poultry producers the option of requiring a set amount of genetic gain for certain traits, such as egg production, according to industry standards.

When using subjective or choice approaches to derive REV, the producer's goals are considered rather than economic decisions alone. An ad hoc approach to subjective methodology, requires producers to rate economically relevant traits (ERT) based on their perceived percentage of trait importance rather than its economic or biological significance (Bourdon, 1998). The percentages of each trait are then made relative to one another using the SD of each trait's progeny differences to produce the index coefficients.

Choice experiments are another common option for the subjective evaluation of REV estimates. Just et al. (2018) used choice experiments to estimate the REV and the marginal willingness to pay of different traits for Brown Swiss cattle operations in different environments. Relative economic values were calculated utilizing data collected from a survey of 18 choice sets with breeding values of 6 trait complexes. Using these resulting REV estimates, Just et al. (2018) designed a total merit index across environments and compared it with the REV of the total merit index utilized at that time. Choice experiments produced REVs similar to those previously calculated by strictly economic methods, though farmers indicated their desire for perinatal sucking behavior to be included as an additional trait in the future. Though not economically significant, perinatal sucking behavior may be important to producers from a management standpoint. Choice experiments are suitable methods for assessing the importance of traits from the producer's perspective, but they must be used cautiously since they are not entirely driven by economic considerations.

Non-objective approaches, specifically choice experiments, have seen a renewed interest in the derivation of REV over the past decade (Duguma et al., 2011; Byrne et al., 2012; Fuerst-Waltl et al., 2016; Gizaw et al., 2018; and Just et al., 2018). Gizaw et al. (2018) argued that non-objective approaches might be effective alternatives to economic analysis in developing countries without adequate economic and production data. These preference-based methods can also increase the producer's commitment to breeding objectives by involving the producer in decisions regarding the selection and weighting of traits, especially in circumstances where producer acceptance may be lacking (Nielsen & Amer, 2007). Just et al. (2018) also suggested that non-objective approaches are of interest because producer's preferences may not be affected by economic factors alone. For example, many livestock producers may emphasize non-economic factors such as animal care and wellbeing, sustainability, and other operation-specific factors over purely economic motives.

Nevertheless, the use of non-objective methods to calculate REV does not qualify as a valid economic selection index and can be misleading, both economically and genetically (Bourdon, 1998). Though non-objective methods can be used with great caution, objective methods should be used to derive REV if the breeder's objective is purely to maximize profit (Just et al., 2018).

Objective

Positive approaches to the assessment of REV are rare since the calculation is based on current and historical records of performance and profit data (Groen, 1989). Regression analysis is performed on the records to determine which traits contribute most to the profitability of the production system and establish a relationship between profitability and the breeding values of observed traits (Gabina et al., 2000). There are 2 significant disadvantages when using this method. The first is traits and prices are based on current records rather than future trends in the industry (Groen, 1989). The second is the large amount of data required from the production system for the regression analysis.

Normative approaches include the use of either profit functions or bioeconomic models (Groen, 1989). Profit functions are single equations representing the correlation between the animal's performance of each ERT and the corresponding measure of the economic outcome (Ponzoni, 1988) In profit functions, the performance of each trait in the breeding objective is used to calculate partial derivatives of profit in a single equation, and each REV is derived as the partial derivative of the function through the relationship between trait performance and profit (Bourdon, 1998).

Profit functions can take on many different forms as livestock systems can be evaluated from different perspectives, which affects the calculation of each traits REV (James, 1982b). For instance, Ponzoni (1988) developed a practical example for deriving REV estimates for the Australian Merino sheep breeding objective. This example evaluated 3 combinations of profit functions: 1) income minus expense, 2) income divided by expense (return on investment), and 3) expense divided by income (cost per unit of production). Each was calculated using production data to evaluate different variations to derive REV (Brascamp et al., 1985; Ponzoni, 1988). According to this study, there was no favored method for calculating economic values, as combining income and expenses in different ways had little effect on selection decisions when only fixed costs were considered (Ponzoni, 1988). The results from the example given by Ponzoni (1988) were consistent with the conclusions drawn in a similar study by Brascamp et al. (1985).

The main benefits of using profit functions to determine REV is the simplicity of calculations and analysis of results. Assuming that the breeder's main objective is profit maximization, profit functions remove the biases and preferences of ranchers, opting for a stricter economic approach to establishing the breeding objective. One disadvantage of this method for REV calculation is traits must be validated monetarily before being included in the profit equation. Additionally, due to the large differences in production schemes and economic environments in the livestock industry, single equation methods may not be the most accurate or flexible model to use in determination of REV for complex systems (Bourdon, 1998),

The use of bio-economic simulation is a normative alternative to profit equations for REV calculation. Though very similar to profit functions, bio-economic models are multi-equation models that simulate economic situations to determine measures of economic efficiency of the chosen production system (Conington, 1999). Through bio-economic modeling, REV estimates are determined as the partial derivatives of the relationship between economic outcomes with simulated changes in the genetic levels of the desired trait. The equations can be classified into different levels, the incorporation of simulation of biological relationships, management decisions, and some measure of economic efficiency, such as profitability (Bourdon, 1998).

Bio-economic models can be grouped into either deterministic or stochastic approaches. Wang and Dickerson (1991) used the deterministic approach to describe lamb and wool production efficiency during the entire production cycle in sheep under genetic management of performance traits. Various management options were used in this trial, including various breeding strategies, weaning ages, feeding rates, and other options. Wang and Dickerson (1991) applied the mean values of genetic input parameters for growth rate, length of anestrus, fertility, number of lambs born, milk yield, mortality, body composition, and wool growth to estimate REV for each trait. In contrast, the stochastic approach describes the animal's performance through the individual's overall mean and variability (Steeneveld et al., 2007). While deterministic models focus on trait means from input parameters alone, the stochastic method accounts for the variability of input parameters. In some instances, stochastic models may provide more useful information, as the probabilities of the potential economic effects may be determined by using trait variability (Steeneveld et al., 2007). For example, Jones et al. (2004) incorporated stochastic methods into the model by including variation between animals at different time points for growth and carcass traits in 1,000 crossbred slaughter lambs. Despite differences, both bio-economic methods simulate characteristics of the production system through mathematical approaches, which may provide useful information for the estimation of REV.

Bio-economic models are much more precise than simple profit equations due to the many equations needed to represent the fundamental biological interactions (Bourdon, 1998). Multiple equations provide more detail than simple profit functions, so one can more accurately determine the impact of a change in a single genetic performance component on the individual's overall profitability. Furthermore, properly designed bioeconomic models can include more flexibility since the adjustment of an input operation within a biological model is relatively simple, rather than changing the whole model to accommodate a new system (Bourdon, 1998).

In contrast, one of the major disadvantages of bio-economic model creation is the high cost of time and money due to the high level of intricacy (Bourdon, 1998). Additionally, the large amount of input information necessary from different operation sectors can be arduous, both to measure and attain from producers. Some authors (i.e., MacNeil et al., 1997) have questioned the use of bioeconomic simulation when calculating REV because the genetic simulation of one trait can change the genetic performance of some other traits in the breeding objective. Ultimately, the change in genetic performance of one trait due to selection of another may indicate that the observed REV estimates do not represent independent changes in each trait. Furthermore, the bio-economic models are designed to mimic specific production and environmental circumstances (e.g., pure-breeding, crossbreeding), but like all models, they are not flexible enough to easily adjust to a different production system once designed. Despite these disadvantages, bioeconomic modeling is a widely utilized method for calculating REV across livestock systems.

In summary, approaches to the development of REVs can be divided into both non-objective and objective methods. Non-objective methods occur through the subjective evaluation of traits and provide producers the opportunity to make decisions regarding the breeding objective. In contrast objective methods are purely economic and occur through mathematical simulations of different production systems. Objective methods can be further separated into positive and normative approaches, with the latter subdivided to include profit functions and bio-economic modeling. While the positive method is based only on current records, normative approaches may be used to assess future pricing based on specific parameters. The normative approaches described above can address a variety of production information in a well-designed model but cannot be used as a 'one size fits all' approach because the parameters change based on different production systems and environments. Overall, the variety of production systems, environments, traits included, and management practices within just the wool industry make an ideal approach to the development of economic values incomprehensible.

Establishing economic values in the wool industry

The establishment of REV estimates for wool traits in the U.S. wool industry is a unique challenge, due to the divergent marketing avenues. Australia's market indicators, the standard for global market prices, have become more influential on American wool prices since the U.S. exports more than 60% of the wool produced domestically (Lupton, 2015; USDA-ERS, 2020). The influence of international marketing indicators and the high percentage of PT sales that are not reported adequately by the USDA makes collecting economic information on fine wool traits difficult. However, domestic wool buyer’s market over 75% of U.S wool, both domestically and internationally, providing a potentially accurate source of domestic wool market data (Lupton, 2008).

Though most U.S. fine wool producers are highly profit driven, there are instances where personal quality preferences may blur bottom line. Burton et al. (2015) published trends in the sheep industry over a 50 yr span, and authors found that, though selection pressures have moved away from wool quality traits, producers continue to select for FD. Producers continued selection of FD indicates that the breeding goals of some U.S. producers may not be strictly profit driven.

Additionally, the U.S. fine wool industry consists of various marketing avenues and breeding goals (NRC, 2008). Apart from the commercial wool clip, some producers may sell wool to small, domestic consumers such as hand spinners and small-scale wool mills, each of which have very different quality requirements, as previously discussed. The various market avenues and requirements further suggest some level of non-objective evaluation should take place in addition to an objective economic assessment during the calculation of REV estimates of fine wool traits. The combination of REV estimation methods will provide the opportunity to objectively evaluate economically driven traits, while also considering traits that may be of functional rather than economic importance.

Once all traits within the breeding objective have accurate estimations of REV, the development of a selection index may take place. Though it may seem like a fairly simple process, the combination and weighting of ERT may cause both statistical and practical issues to arise (Just et al., 2018). For example, some traits included may not have been validated monetarily or there may be insufficient records from lack of data collection or information. Issues may also occur when the breeders' preferences do not match with the objective of profit maximization (Pearson, 1982). When these issues arise, the estimation of required parameters becomes difficult. However, if difficulties of REV estimation can be addressed, a well-designed selection index may be an effective tool to maximize the selection response and profitability of a selection program.

Selection indices: theory, development, utilization

As discussed in the previous section, breeding objectives define traits of importance and guide the direction of genetic improvement, which are utilized in selection index methodology to create the aggregate genotype (MacNeil et al., 1997). After defining breeding objectives, the design of the index requires the estimation of 4 important parameters. The first is the phenotypic variance or SD of each trait, which is utilized for the development of the P matrix and estimates genetic variance (MacNeil et al., 1997). The second is the estimation of both phenotypic and genetic correlations between traits. Genetic and phenotypic correlations will allow for the weighting of economic values as these correlations explain how, and to what extent, improvement of one trait will have on the other (MacNeil et al., 1997). Third is heritability, a parameter used to calculate genetic variance and estimate how each trait will respond to genetic selection. Lastly, are the estimates of REV, as this explains the emphasis given to each trait in the index (MacNeil et al., 1997). For instance, giving more emphasis to a trait with a lower economic value may cause profit losses over time. Along with breeding objectives, it is the REV that provides direction to a selection program. After these four parameters are estimated, the selection index can be created, through the mathematical procedures of matrix algebra.

The basis of selection index theory and its mathematical principles were primarily developed in the early half of the 20th century (Hazel and Lush, 1943; Wilton and Van Vleck, 1968; MacNeil et al., 1997; Borg et al., 2009; Oldenbroek and Waaij, 2015; and Oschner et al., 2017). The development of this theory was concurrent with other significant advances in genetics, such as the foundation of population genetics and the discovery that phenotypic diversity in a trait depends on multiple genes. However, the foundation for selection index theory was set long before then, going back to the origins of animal breeding.

Selection index theory development

Many academic animal breeders ask how to reach an optimal selection level, based on the phenotypic and genetic information, for a phenotype composed of multiple traits (Walsh and Lynch, 2000). Researchers proposed many methods to assist with multiple-trait selection, but they may not exhibit equal efficiency (Hazel and Lush, 1942). In their research, Hazel and Lush (1942) analyzed 3 conventional methods of selecting for net merit, designated as tandem selection, total score, and independent culling methods. Tandem, or sequential selection, is defined by selecting one trait per generation until each trait is improved to the desired level. Independent culling levels, a process by which a level of merit is established for each trait, culls any animal under the established level regardless of other attributes' merit. The third method evaluated in Hazel and Lush (1942) is the total score method, which selects traits concurrently using an index that gives some credit or discount to each animal according to the advantage or disadvantage of its traits.

Hazel and Lush (1942) examined these different methods under the simplified assumption that the characters (n) under selection are independent, and of an equal weighting based on the REV, heritability, and SD. Under these assumptions, the authors compared the 3 methods described above by method efficiency. The efficiency of each method was calculated by multiplying each trait's expected improvement by its REV, and maximum efficiency was determined by the maximum level of genetic improvement per unit of time and labor expended (Hazel and Lush, 1942). Tandem selection is the simplest way to select for multiple characteristics, but it is the least efficient selection method. Hazel and Lush (1942) reported that independent culling levels have an intermediate efficiency between the tandem selection and total score methods if compared at the maximum efficiency possible. Though not as efficient, the independent culling method may have reduced costs compared to the total score approach, in which selection cannot occur until all the traits are measured (Walsh and Lynch, 2000). The total score method is the most efficient provided the index gives proper weight to each character. Based on n equally important uncorrelated characters, the total score approach is $\sqrt{n}$ times more efficient than tandem selection. As a result, the total score method (index selection) remains a more efficient selection tool for producers (Hazel and Lush, 1942).

Selection index creation

In the following year, Hazel (1943) expounded on the total score method, now designating the method as selection index, and first applied index principles to livestock. The purpose of developing selection indices is to maximize genetic improvement toward an identified economic selection criterion and evaluate animals for multiple characteristics simultaneously (Hazel et al., 1994). It is known that selection for the enhancement of an animal's genotype is proportional to the improvement of a population's phenotype (Hazel, 1943). Multiple traits and their associated degree of economic importance influence this genetic improvement and make up the animal's practical value. The aggregate genotype is defined as the sum of the animal's genetic values for multiple traits, with each genetic value weighted according to each trait's REV (Hazel, 1943). The aggregate genotype (breeding objective) integrates different trait information into a single value (H) and can be specified as:

Equation 1.1) Aggregate genotype estimation

$$H = v_1 a_1 + \ v_2 a_2 + \cdots + v_n a_n$$

Where H is the aggregate genotype, v represents the REV for each trait, a is the additive genetic value, and n represents the number of traits in the breeding objective.

Due to environmental factors and non-additive genetic effects, an animal's phenotype may diverge from its genotype. For this reason, the exact breeding value for each trait in the breeding objective cannot be identified without error and selection must be practiced indirectly using predictors of the breeding value (Hazel, 1943). Based on phenotypic performance for each animal's traits, a correlated variable (I) must be used to create a selection index properly. The index equation I is defined as:

Equation 1.2) Selection index estimation

$$I = b_1 X_1 + \ b_2 X_2 + \cdots + b_n X_n$$

where, I represents the index value, X is the vector of values from a selection criterion (phenotype, EBV, etc.) for each trait, and b represents the relative index weights. While equation 1.1 is composed of traits within the breeding objective, the selection criterion's traits are depicted within equation 1.2 (Bourdon, 1998). Depending on accessible information, the traits in these 2 different equations may be the same or different. The breeding objective and selection criterion are often not the same because some ERT are difficult for producers to record and collect (Goddard, 1998).

Researchers must calculate relative index weights from the index (equation 1.2) to gain unbiased estimates of the aggregate genotype (equation 1.1; Hazel, 1943). Computation of index weights begin with maximization of the correlation between H and I (R_{HI}), which can be derived in matrix notation below:

Equation 1.3) Maximization of the correlation between H and I

$$Gv = Pb$$

where, G is a n x m matrix of genetic (co)variances for all m traits and P represents a n x n matrix of phenotypic (co)variances between the traits evaluated and available as the selection criteria (MacNeil et al., 1997). The formulation of index weights can then be obtained as the equation is solved below:

Equation 1.4) Index weight estimation

$$P^{-1}Gv = b$$

Selection index derivation requires the utilization of phenotypic and genetic information to provide the maximum association between expected (equation 1.2) and true breeding values (equation 1.1; James, 1982a). Index weights derived via equation 1.3 and 1.4 necessitate the use of phenotypic variance or SD, phenotypic and genetic correlations, and heritability to create estimates of P and G (MacNeil et al., 1997). These statistics can be obtained through reported estimates in scientific literature or calculated explicitly for a population if sufficient data is available.

With an optimal index, accurate calculations of the P and G matrix components enhance response to selection and increased selection intensity (James, 1982a). In practice, the components of P and G matrices and REV are estimated and subject to sampling errors, leading to overall index efficiency losses. However, it should be noted that minor errors for either economic values or genetic parameters have shown relatively little effect on the genetic gain and losses in selection efficiency (Vandepitte and Hazel, 1977; MacNeil et al., 1997).

The selection index calculation method discussed above assumes that selection is based on phenotype to improve genetic merit (MacNeil et al., 1997). Bourdon (1998) identified that this formulation has 2 key drawbacks. The first is the method's lack of accuracy due to lack of pedigree information. The second, is this method does not account for genetic differences among contemporary groups and is therefore, biased. Because of these shortcomings, a more robust statistical methodology has been adopted using genetic predictions derived from multi-trait Best Linear Unbiased Prediction (BLUP) rather than individual phenotypic information (MacNeil et al., 1997). Best Linear Unbiased Prediction accounts for non-random mating and bias difficulties, increases the accuracy through the inclusion of information on relatives, and automatically accounts for the effect of environmental factors (Falconer and Mackay, 1996). Henderson (1963) observed that genetic predictions could be substituted for true breeding values in the aggregate genotype if all objective breeding traits have available estimates derived from multi-trait BLUP analysis. This formulation is demonstrated below:

Equation 1.5) Index value estimation using estimated breeding values

$$I = v'\hat{u}$$

where, $\hat{u}$ is a vector of the EBV or expected progeny difference for an individual. In practice, a more likely case is that not all traits in the breeding objective will have predicted breeding values available (Schneeberger et al., 1992). In this case, the formulation is shown below:

Equation 1.6) Index value estimation using expected breeding values and index coefficients

$$I = b'\hat{u}$$

Index coefficients (b) of this type of index can be derived as

Equation 1.7) Index coefficient estimation

$$b = G_{12}{G_{11}}^{-1}v$$

where G_{12} is an *n* x *m* matrix of genetic (co)variance between selection criteria in the index and traits in the breeding objective and G_{11} is an *n* x *n* matrix of genetic (co)variances of the selection criteria in an index. Through unbiased estimation of (co)variances by BLUP, indices can account for a large amount of information on relatives, which increases the accuracy of prediction (Bourdon, 1998).

The selection index allows producers to make unbiased judgments on their livestock based on multiple traits that give appropriate emphasis to genetic gain and economic impact (Hazel, 1943). Additionally, index selection allows for data to be taken from different sources while simultaneously accounting for accuracy variations. Based on the emphasis of economic importance and genetic gain, producers are compelled to accurately assess the animal's practical value rather than phenotypic assessment (Harris, 1970). Index selection is a valuable tool for producers due to the focus on genetic improvement of the animal through emphasis on traits that are of economic value.

Selection index utilization

Since the initial conception of selection indices in the early 1900s, many livestock species, breeds, and operations have implemented their use to improve performance and response to selection through genetic means. In sheep, selection index programs have been successfully implemented around the world for many different objectives, such as lean growth, prolificacy, and wool production.

Simm et al. (2002) reported results from 9 yr of index selection in Suffolk sheep in Scotland, which were selected to improve carcass lean and fat weight based on a desired gains approach as opposed to profit equations using actual market information. The traits recorded included fat depth, muscle depth, and live weight and showed substantial responses to selection compared to the control flock, with the index flock having an average of 40 g/kg more lean carcass and 48 g/kg less carcass fat each year compared to the control flock.

Conington et al. (2001) created three different indexes based on three different production types of the United Kingdom's hill sheep flocks: 1) intensive, where lambs are either kept as replacements or sold to slaughter, 2) extensive, where lambs are sold to finishing operations before slaughter, and 3) semi-intensive, where some lambs are finished and sold to slaughter and others may be taken to finishing operations. The main goal of this selection program was to incorporate the genetic improvement of both carcass and maternal traits into selection programs, and for that reason, three indices were deemed appropriate due to the diversity among the different production systems (Conington et al., 2001). Each index included 2 groups of traits categorized into maternal and lamb production traits. Conington et al. (2001) analyzed the expected genetic change between all 3 index types and found that greater responses were observed in the intensive operations, whereas the extensive operations observed the lowest response to selection. The lower response of the extensive operations were due to the lower level of lamb output that reduced monetary gains and thus economic weights as compared to the intensive operation.

Mortimer et al. (2010) examined the effects of selection for both visual and measured traits, using standard MERINOSELECT indices and visual scorecards. MERINOSELECT, produced by Sheep Genetics (Sheep Genetics, NSW, Australia) provides Australian producers with selection indices that cover multiple breeding objectives. Mortimer et al. (2010) created 5 different Merino breeding objectives based on either Merino or dual-purpose breeding, with various levels of micron premium: 1) Merino, 14%, 2) Merino, 7%, 3) Merino, 3.5%, 4) dual purpose, 7%, and 5) dual purpose, 3.5%. The breeding objectives included 13 wool traits, along with number of lambs born and BW measurements. The analysis followed predicted genetic responses of all traits, including the selection of visual traits, for 10 yr of selection. Based on 10 yr of selection of the standard MERINOSELECT indices the predicted responses of visual traits when included in the index showed great improvement, in most cases doubling the change that would have occurred if not included in the selection criteria. For instance, in the 14% Merino group, wool handle improved from a score of -0.52 when not included in the selection criteria to -0.73 when it was included. In most cases, Mortimer et al. (2010) observed similar results that indicate selection using MERINOSELECT indices may result in a favorable correlated response in visual traits, such as character and color.

These studies suggest that, if developed properly, index selection can be a useful tool in the genetic improvement of sheep. Further, evaluation of the studies above indicated that selection index programs can be successfully implemented in a wide range of production scenarios. However, it is essential to include the proper traits in the breeding objective in order to have meaningful genetic improvement.

Conclusions

Overall, selection indices can be a valuable tool for producers to enhance the response to selection and improve the genetics of a population of animals for a specific goal, such as wool production. A selection index can be properly developed through the careful analysis of genetic parameters, phenotypic variance components, and REV estimations. However, when the traits considered for the index have been calculated into EBV measures through the NSIP multi-trait genetic evaluation, the aggregate breeding value may be used with individual EBV measures and REV estimations (Bourdon, 1998). Generally, the index goal is to maximize the profits, production, and quality of U.S. fine wool. However, the lack of recorded traits (e.g., CFW) and range of profit and quality drivers across operations may necessitate economic and producer emphasis when calculating REV estimates.

Within the U.S., efforts towards the genetic improvement of the sheep and wool industries have primarily been driven by NSIP. Founded in 1986, the NSIP was created to provide an economic genetic evaluation tool by converting of performance records into flexible decision-making tools for selection by U.S. sheep producers (Wilson and Morrical, 1991). The NSIP began operating a genetic evaluation program in 1987, focused on single-trait, within-flock selection for Targhee sheep, which shifted to across-flock selection in 1995, in conjunction with the Suffolk breed (Notter, 1998). Later, Borg (2004) developed the WRI with the inclusion of wool production traits, though little emphasis was placed on fine wool production. With the aim of improving quality and productivity of fine wool sheep, the Fine Wool Consortium (FWC) was formed in 2016. The roadmap laid out by the FWC addressed the need for an index that focuses primarily on production efficiency and profit maximization of fine wool traits in the U.S., due to the lack of emphasis on quality fine wool production in other indices provided by NSIP.

In comparison, global leaders, such as Australia, have multiple selection indices with emphasis on fine wool production that have been used for over 15 yr (Brown et al., 2007). In 2005, Sheep Genetics Australia developed MERINOSELECT indexes to target genetic improvement of Australian Merino flocks, whether producers focus on maternal, terminal, or wool production. The selection indices available have micron premium options, with the selection index having the lower micron premium putting more emphasis on FW and the higher on reduced FD (Brown et al., 2007). Australian producers have effectively utilized genetic selection programs such as MERINOSELECT, to grow high-quality wool, which has aided in maintaining Australia's global wool market dominance. If the U.S. wool producers desire to become more competitive in the global wool market, genetic selection programs emphasizing wool production should be implemented.

References

Amer P. R. 1999. Economic accounting of numbers of expressions and delays in sheep genetic improvement. New Zealand J. Agric. Res. 42:325-336.

American Sheep Industry (ASI). 2014. Code of practice for preparation of wool clips. American Sheep Industry, Englewood, CO. Available from: http://d1cqrq366w3ike.cloudfront.net/http/DOCUMENT/SheepUSA/Code_of_Practice_low.pdf (Accessed 19 June 2021.)

ASI. 2021. Wool trust report 2019-20. USDA-NASS. Washington, D.C. Available from: https://www.ams.usda.gov/reports/wool-trust (Accessed 20 March 2021.)

Anderson, D. P., O. Capps, E. E. Davis, and S. D. Teichelman. 2009. Wool price differences by preparation in the United States. Sheep Goat Res. J. 24:1-9.

Atkins, K. D. 1997. Genetic improvement of wool production. In: L. Piper and A. Ruvinsky, Eds., The genetics of sheep. CAB International, Oxon, US. p. 471-504.

Australia Wool Innovation (AWI). 2004. The China – Australia Free Trade Agreement Feasibility Study. Australia Wool Innovation Ltd. Sydney, NSW, Australia. Available from: https://www.dfat.gov.au/sites/default/files/cfta_submission_2ag17.pdf (Accessed 5 February 2022.)

AWI. 2013. Visual sheep scores. Australia Wool Innovation Ltd. Sydney, NSW, Australia. Available from: https://www.wool.com/globalassets/wool/market-intelligence/woolcheque/characteristics/visual_sheep_scores_researcher_version_lr.pdf (Accessed 3 June 2021.)

Baxter, B. P. 1993. Influences on comparisons between the mean fibre diameter of wools measured by airflow and by projected image methods. IWTO Report No. 13. Istanbul, Turkey. Available from: https://www.researchgate.net/publication/237739867_INFLUENCES_ON_COMPARISONS_BETWEEN_THE_MEAN_FIBRE_DIAMETER_OF_WOOLS_MEASURED_BY_AIRFLOW_AND_BY_PROJECTED_IMAGE_METHODS (Accessed 31 May 2021.)

Baxter, B. P. and D. J. Cottle. 1998. The use of midside fleece fibre diameter distribution measurements in sheep selection. Wool Tech. Sheep Breed. 46(2):154-171. Available from: http://sheepjournal.net/index.php/WTSB/article/view/1430 (Accessed 19 May 2021.)

Beattie, A. W. 1961. Relationships among productive characters of Merino sheep in north-western Queensland. 1. Estimates of phenotypic parameters. Queensland J. Agri. Sci. 18:437-445.

Borg, R. C., D. R. Notter, L. A. Kuehn, and R. W. Kott. 2007. Breeding objectives for Targhee sheep. J. Anim. Sci. 85:2815-2829. doi: https://doi.org/10.2527/jas.2006-064

Borg, R. C. 2004. Breeding objectives for Targhee sheep. MS Thesis. Virginia Polytechnic Institute and State Univ., Blacksburg.

Borg, R. C., D. R. Notter, and R. W. Kott. 2009. Phenotypic and genetic association between lamb growth traits and adult ewe body weights in western range sheep. J. Anim. Sci. 87:3506-3514.

Botha, A. F. and L. Hunter. 2010. The measurement of wool fibre properties and their effect on worsted processing performance and product quality. Part 1: The objective measurement of wool fibre properties. Text. Prog. 42 (4):227-339. doi: http://dx.doi.org/10.1080/00405167.2010.486932

Bourdon, R. M. 1998. Shortcomings of current genetic evaluation systems. J. Anim. Sci. 76:2308-2323. doi: https://doi.org/10.2527/1998.7692308x

Brascamp, E. W., C. Smith, and D. R. Guy. 1985. Derivation of economic weights from profit functions. Anim. Prod. 40:175-180. doi: https://doi.org/10.1017/S0003356100031986

Brash, L. D., P. J. Taylor, and A. R. Gilmour. 1997. Estimates of genetic parameters and environmental effects for production traits in young Merino rams. Proc. Assn. Adv. Anim. Breed. Genet. 12:529-533. Available from: http://www.aaabg.org/livestocklibrary/1997/AB97115.pdf (Accessed 15 May 2021.)

Brester, G. 2018. Wool profile. Agriculture marketing resource center. Available from: https://www.agmrc.org/commodities-products/livestock/lamb/wool-profile (Accessed 15 March 2021.)

Bromley, C. M., G. D. Snowder, and L. D. Van Vleck. 2000. Genetic parameters among weight, prolificacy, and wool traits of Columbia, Polypay, Rambouillet, and Targhee sheep. J. Anim. Sci. 78:846-858. doi: https://doi.org/10.2527/2000.784846x

Brown, D. J., A. Ball, R. Mortimer, and M. Oppenheimer. 2002a. Incorporating subjectively assessed sheep and wool traits into genetic evaluations for Merino sheep. 2: Phenotypic variation and heritabilities. Wool Tech. Sheep Breed. 50(3):373-377.

Brown, D. J., A. Ball, R. Mortimer, and M. Oppenheimer. 2002b. Incorporating subjectively assessed sheep and wool traits into genetic evaluations for Merino sheep. 2: Phenotypic and genetic correlations. Wool Tech. Sheep Breed. 50(3):378-382.

Brown, D. J., A. E. Huisman, A. A. Swan, H. U. Graser, R. R. Woolaston, A. J. Ball, K. D. Atkins, and R. G. Banks. 2007. Genetic evaluation for the Australian sheep industry. Proc. Assoc. Advmt. Anim. Breed. Genet. 17:187-194. Available from:

https://www.academia.edu/download/43450546/Genetic_evaluation_for_the_Australian_sh20160307-9576-wlntey.pdf (Accessed 13 June 2021.)

Brown, D., A. Swan, K. Bunter, A. McMillan, and R. Banks. 2016. Genetic evaluation for the Australian sheep industry: Better targeted and faster genetic gain. Meat and Livestock Australia Limited. North Sydney, NSW. Available from: https://www.mla.com.au/contentassets/ff67f09c82af402fab4b7951ce982322/b.sgn.0127_final_report_.pdf (Accessed 15 March 2021.)

Burton, D. J., P. A. Ludden, R. H. Stobart, and B. M. Alexander. 2015. 50 years of the Wyoming ram test: How have sheep changed. J. Anim. Sci. 93:1327–1331. doi: https://doi.org/10.2527/jas.2014-8150

Byrne, T. J., P. R. Amer, P. F. Fennessy, P. Hansen, and B. W. Wickham. 2012. A preference-based approach to deriving breeding objectives: applied to sheep breeding. Animal 6(5):778-788. doi: 10.1017/S1751731111002060

Cloete, S. W. P., A. R. Gilmour, J. J. Olivier, and J. B. van Wyk. 2003. Age trends in economically important traits of Merino ewes subjected to 10 years of divergent selection for multiple rearing ability. S. Afr. J. Anim. Sci. 33:43-51. doi: 10.4314/sajas.v33i1.3737

Conington, J. 1999. The genetic improvement of carcass and maternal traits in Scottish Blackface sheep. Ph.D. Thesis, Univ. of Edinburgh, Scotland, U. K.

Conington, J., S. C. Bishop, B. Grundy, A. Waterhouse, and G. Simm. 2001. Multi-trait selection indexes for sustainable UK hill sheep production. Anim. Sci. 73:413-423. doi: 10.1017/S1357729800058380

Cottle, D. J. 2010. Wool preparation, testing and marketing. In: D. J. Cottle, Ed., Int. Sheep and Wool Handbook. Nottingham University Press, Nottingham, UK. p. 581- 618.

Cottle, D. J., and B. P. Baxter. 2015. Wool metrology research and development to date. Text. Prog. 47(3):163-315. doi: https://doi.org/10.1080/00405167.2015.1108543

Couchman, B. 2012. Demand for Australian wool. In: Wool marketing and clip preparation. The Australian wool education trust licensee for educational activities University of New England. Australian Wool Exchange Limited, Australia. 18:1-16. Available from: http://www.woolwise.com/wp-content/uploads/2017/07/WOOL-422-522-12-T-18.pdf (Accessed 15 April 2021.)

Cozzolino, D., F. Montossi, and R. San Julian. 2005. The use of visible and near infrared reflectance spectroscopy to predict fibre diameter in both clean and greasy wool samples. Anim. Sci. 80:333-337. doi: https://doi.org/10.1079/ASC41760333

D'Arcy, J. B. 1990. Sheep management and wool technology. 3rd ed. New South Wales University Press, Kensington, NSW Australia. p. 85-94.

Di, J., Y. Zang, K. C. Tian, Lazate, J. F. Liu, X. M. Xu, Y. J. Zhang, and T. H. Zhang. 2011. Estimation of (co)variance components and genetic parameters for growth and wool traits of Chinese superfine merino sheep with the use of a multi-trait animal model. Livest. Sci. 138:278-288. doi: http://dx.doi.org/10.1016/j.livsci.2011.01.005

Doyle, E. K., J. W. V. Preston, B. A. McGregor, and P. I. Hynd. 2021. The science behind the wool industry. The importance and value of wool production from sheep. Anim. Front. 11:16-23. doi: 10.1093/af/vfab005

Duguma, G., T. Mirkena, A. Haile, A. M. Okeyo, M. Tibbo, B. Rischkowsky, J. Solkner, and M. Wurzinger. 2011. Identification of smallholder farmers and pastoralists' preferences for sheep breeding traits: choice model approach. Animal 5(12):1984-1992. doi: 10.1017/S1751731111001029

Dyer, J. M., S. D. Bringans, G. D. Aitken, N. I. Joyce, and W. G. Bryson. 2007. Extraction and characterization of nonscourable chromophores from discoloured fleece wool. Color. Technol. 123:54-58. doi: 10.1111/j.1478-4408.2006.00060.x

Erdogan, U. H., Y. Seki, and F. Selli. 2020. Wool fibres. In: R. M. Kozlowski and M. M. Talarczyk, Eds., Handbook of natural fibres. Woodhead Publishing. 2:257-278. doi: https://doi.org/10.1016/B978-0-12-818398-4.00011-6

Falconer, D. S. and T. F. C. Mackay. 1996. Introduction to quantitative genetics. 4th ed. Longmans Green, Harlow, Essex, UK. p. 240-245.

Ferrero-Regis, T. 2020. From sheep to chic: Reframing the Australian wool story. J. Aust. Stud. 44:48-64. doi: https://doi.org/10.1080/14443058.2020.1714694

Fogarty, N. M. 1995. Genetic parameters for live weight, fat and muscle measurements, wool production and reproduction in sheep: a review. Anim. Breed. Abstr. 63:101.

Fuerst-Waltl, B., C. Fuerst, W. Obritzhauser, and C. Egger-Danner. 2016. Sustainable breeding objectives and possible selection response: Finding the balance between economics and breeders' preferences. J. Dairy Sci. 99:9796-9809. doi: https://doi.org/10.3168/jds.2016-11095

Gabina, D., E. Ugarte, and P. Santamaria. 2000. The definition of breeding objectives in the Latxa dairy sheep breed. Options Méditerranéennes: Série A. 43:19-25.

Giebel, G. 2020. World wool market. ASI annual convention. Scottsdale, AZ. Available from: https://www.sheepusa.org/wp-content/uploads/2020/02/World-Wool-Market-Update-Goetz-Giebel-ASI-Consultant.pdf (Accessed 14 March 2021.)

Gillespie, D. T. C. 1948. Wool Wax. A review of its properties, recovery and utilization. J. Text. Inst. Proc. 39(2):45-85. doi: 10.1080/19447014808663117

Gizaw, S., A. Abebe, A. Bisrat, T. Zewdie, and A. Tegene. 2018. Defining smallholders' sheep breeding objectives using farmers trait preferences versus bio-economic modelling. Livest. Sci. 214:120-128. doi: https://doi.org/10.1016/j.livsci.2018.05.021

Goddard, M. E. 1998. Consensus and debate in the definition of breeding objectives. J. Dairy Sci. 81(2):6-18. doi: https://doi.org/10.3168/jds.S0022-0302(98)70150-X

Grasso, V. 2014. The Berry Amendment: Requiring defense procurement to come from domestic sources. Congressional Research Service, Washington, DC. Available from: https://apps.dtic.mil/sti/citations/ADA599539 (Accessed 19 April 2021.)

Groen, A. F. 1989. Cattle breeding goals and production circumstances. Ph.D. Diss., Agric. Univ., Wageningen, The Netherlands.

Groen, A. F., T. Steine, J. Colleau, J. Pedersen, J. Pribyl, and N. Reinsch. 1997. Economic values in dairy cattle breeding, with special reference to functional traits. Report of an EEAP-working group. Livest. Prod. Sci. 49:1-21. doi: https://doi.org/10.1016/S0301-6226(97)00041-9

Hanford, K. J., L. D. Van Vleck, and G. D. Snowder. 2003. Estimates of genetic parameters and genetic change for reproduction, weight, and wool characteristics of Targhee sheep. J. Anim. Sci. 81:630-640. doi: https://doi.org/10.2527/2003.813630x

Harris, D. L. 1970. Breeding for efficiency in livestock production: defining economic objectives. J. Anim. Sci. 30:860-865. doi: https://doi.org/10.2527/jas1970.306860x

Harwood, R. and E. Smith. 2020. Testing of natural textile fibers. In: R. M., Kozlowski, and M. Mackiewicz-Talarczyk, Eds., Handbook of natural fibres. 2nd ed. Elsevier Science, Amsterdam, Netherlands. p. 535-576.

Hatcher, S. and K. D. Atkins. 2000. Breeding objectives which include fleece weight and fiber diameter do not need fiber curvature. Asian-Aust. J. Anim. Sci. Supplement A:293-296. Available from: https://www.researchgate.net/profile/Sue-Hatcher/publication/266089617_Breeding_Objectives_which_Include_Fleece_Weight_and_Fibre_Diameter_do_not_Need_Fibre_Curvature/links/54c6bc1c0cf238bb7d098028/Breeding-Objectives-which-Include-Fleece-Weight-and-Fibre-Diameter-do-not-Need-Fibre-Curvature.pdf (Accessed 2 April 2022.)

Hatcher, S., K. D. Atkins, and K. J. Thornberry. 2008. Strategic use of sheep coats can improve your economic return. Aust. J. Exp. Agric. 48:762-767. doi: https://doi.org/10.1071/EA08036

Hazel, L. N. and J. L. Lush. 1942. The efficiency of three methods of selection. J. Hered. 33: 393-399.

Hazel, L. N. 1943. The genetic basis for constructing selection indexes. Genetics. 28:476-490.

Hazel, L. N., G. E. Dickerson, and A. E. Freeman. 1994. The selection index—Then, now, and for the future. J. Dairy Sci. 77:3236-3251. doi: https://doi.org/10.3168/jds.S0022-0302(94)77265-9

Henderson, C. R. 1963. Selection index and expected genetic advance. In: W. D. Hanson and H. F. Robinson, Eds., Statistical Genetics and Plant Breeding. NAS, NRC, Washington, DC. p. 141-163.

Huisman, A. E., D. J. Brown, A. J. Ball, and H. U. Graser. 2008. Genetic parameters for bodyweight, wool, and disease resistance and reproduction traits in Merino sheep. 1. Description of traits, model comparison, variance components and their ratios. Aust. J. Exp. Agric. 48:1177-1185. doi: https://doi.org/10.1071/EA08119

Huisman, A. E. and D. J. Brown. 2008. Genetic parameters for bodyweight, wool, and disease resistance and reproduction traits in Merino sheep. 2. Genetic relationships between bodyweight traits and other traits. Aust. J. Exp. Agric. 48:1186-1193. doi: 10.1071/EA08120

Huisman, A. E. and D. J. Brown. 2009. Genetic parameters for bodyweight, wool, and disease resistance and reproduction traits in *Merino* sheep. 4. Genetic relationships between and within wool traits. Anim. Prod. Sci. 49:289-296. doi: https://doi.org/10.1071/EA08173

Iman, N. Y., C. L. Johnson, W. C. Russell, and R. H. Stobart. 1992. Estimation of genetic parameters for wool fiber diameter measures. J. Anim. Sci. 70:(4)1110-1115. doi: https://doi.org/10.2527/1992.7041110x

IWTO. 2021. Market Information. 16th ed. International Wool Textile Organisation. Brussels, Belgium. Available from: https://iwto.org/resources/statistics/ (Accessed 10 May 2021.)

James J. W. 1982a. Construction, uses, and problems of multitrait selection indices. Proc. 2nd World Cong. Genet. Appl. Livest. Prod. 9:470-478. Available from: http://www.wcgalp.org/system/files/proceedings/1982/construction-uses-and-problems-multitrait-selection-indices.pdf (Access 6 August 2020.)

James J. W. 1982b. Economic aspects of developing breeding objectives: general considerations. In: Barker J. S. F., Hammond K., and McClintock A. E., Future developments in the genetic improvement of animals. Academic Press, Sydney, Australia. p. 107-118.

Johnson, C. L. and S. A. Larsen. 1978. Clean wool determination of individual fleeces. J. Anim. Sci. 47:41-45. doi: https://doi.org/10.2527/jas1978.47141x

Jones H. E., P. R. Amer, R. M. Lewis, and G. C. Emmans. 2004. Economic values for changes in carcass lean and fat weights at a fixed age for terminal sire breeds of sheep in the UK. Livest. Prod. Sci. 89:1-17. doi: https://doi.org/10.1016/j.livprodsci.2004.02.002

Just A., R. Wellmann, and J. Bennewitz. 2018. Estimation of relative economic weights and the marginal willingness to pay for breeding traits of Brown Swiss cattle using discrete choice experiments. J. Dairy Sci. 101:5207-5213. doi: https://doi.org/10.3168/jds.2017-14012

Kelly, R. W., I. Macleod, P. Hynd, and J. Greeff. Nutrition during fetal life alters annual wool production and quality in young Merino sheep. Aust. J. Anim. Sci. 36(3):259-267. Available from: https://ksu-illiad-oclc-org.er.lib.k-state.edu/illiad/illiad.dll?Action=10&Form=75&Value=1057797 (Accessed 27 March 2022.)

Keogh, M. J. and E. M. Roberts. 1985. Near infrared measurement of greasy wool for sheep breeders. Wool Tech. Sheep Breed. 33(3):108-112. Available from: http://www.sheepjournal.net/index.php/WTSB/article/view/931 (Accessed 19 May 2021.)

Kott, R. W., R. H. Stobart, C. M. Hoaglund, C. L. Johnson, B. A. Cameron, and V. M. Thomas. 1992. Effects of skirting on processing characteristics of Targhee wool. J. Anim. Sci. 70:640-645. doi: https://doi.org/10.2527/1992.703640x

Kott, R. W. 1993. Wool grading. Montguide. Bozeman, MT. p. 1- 4. Available from: https://pdf4pro.com/cdn/montguide-msu-extension-534fd9.pdf (Accessed 25 May 2021.)

Kumar, P. S. and S. Suganya. 2017. Introduction to sustainable fibres and textiles. In: Muthu SS (ed) Sustainable fibres and textiles, Woodhead Publishing, Duxford. p. 1-18. doi: 10.1016/B978-0-08-102041-8.00001-9

Lee, G. J., K. D. Atkins, and A. A. Swan. 2002. Pasture intake and digestibility by young and non-breeding adult sheep: the extent of genetic variation and relationships with productivity. Livest. Prod. Sci. 73:185-198. doi: https://doi.org/10.1016/S0301-6226(01)00244-5

Liu, H., Z. Zhou, and B. Malcolm 2011. 2. China's wool import demand: Implications for Australia. Aust. Agribus. Rev. 19:16-34. Available from: https://ageconsearch.umn.edu/record/125703/files/Liu_Zhou_Malcolm.pdf (Accessed 25 May 2021.)

Lockart, L. W. and H. R. Philpotts. 1954. Fleece density grading of Merino sheep. Aust. Vet. J. 30:262-265. doi: https://doi.org/10.1111/j.1751-0813.1954.tb05417.x

Longworth, J., Brown C., and Waldron S. 2010. Chinese sheep and wool industries. In: Cottle, D. J., Ed., International Sheep and Wool Handbook, Nottingham University Press, Nottingham.

Lunney, H. W. M. 1983. Distribution of fiber diameter in wool tops. Text. Res. J. 53:281-289. doi: https://doi.org/10.1177%2F004051758305300504

Lupton, C. J. 1987. The role of objective measurements in wool research and marketing. SID Res. Dig. 3(3):21-25.

Lupton, C. J., F. A. Pfeiffer, and N. E. Blakeman. 1989. Optimizing the value of grease wool through preparation and marketing. SID Res. J. 5(Special Edition):1-20.

Lupton, C. J., F. A. Pfeiffer, N. E. Blakeman, D. N. Ueckert, and J. E. Huston. 1992. Effects of skirting on yield, fineness, and value of wool from fine-wool range ewes. J. Anim. Sci. 70:3657-3664. doi: https://doi.org/10.2527/1992.70123657x

Lupton, C. J. 2008. ASAS CENTENIAL PAPER: Impacts of animal science research on United States sheep production and predictions for the future. J. Anim. Sci. 86:3252-3274. doi: 10.2527/jas.2008-1148

Lupton, C. J. 2011. Wool: skirting, classing, and marketing. Ency. Anim. Sci. 2:1109-1112. doi: 10.1081/E-EAS2-120019849

Lupton, C. J. 2015. Wool chapter. In: SID sheep production handbook, vol. 8, 2015 Edition. American Sheep Industry Association, Fort Collins, CO. p. 1001-1064.

Ma, G. W., Y. K. Chu, W. J. Zhang, F. Y. Qin, S. S. Xu, H. Yang, E. G. Rong, Z. Q. Du, S. Z. Wang, H. Li, and N. Wang. 2017. Polymorphisms of FST gene and their association with wool quality traits in Chinese Merino sheep. PLOS ONE. 12(4):1-12, e0174868. doi: https://doi.org/10.1371/journal.pone.0174868

MacNeil M. D., R. A. Nugent, and W. M. Snelling. 1997. Breeding for profit: an introduction to selection index concepts. Range Beef Cow Symposium. 142. Available from: https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1141&context=rangebeefcowsymp (Accessed 15 November 2019)

Macpherson, S. 2012. Wool classing. In: Wool marketing and clip preparation. The Australian wool education trust licensee for educational activities University of New England. Australian Wool Exchange Limited, Australia. 5:1-42. Available from: https://www.woolwise.com/wp-content/uploads/2017/07/WOOL-422-522-12-T-05.pdf (Accessed 18 May 2021.)

Mahar, T. 2009. Fiber diameter. In: Wool biology and metrology. The Australian wool education trust licensee for educational activities University of New England. Australian Wool Exchange Limited , Australia. 9:1-32. Available from: http://www.woolwise.com/wp-content/uploads/2017/07/WOOL-472-572-12-T-09.pdf (Accessed 26 April 2021.)

Marshall, F. R. and L. L. Heller. 1915. The Woolgrower and Wool Trade. USDA. Bull. No. 206. Washington, D.C. Available from:

https://books.google.com/books?id=JjRUxe4HzlcC&printsec=frontcover&source=gbs_atb#v=onepage&q&f=false (Accessed 10 February 2022.)

McGregor, B. A., A. Doughty, J. Thompson, M. Naebe, and D. Tester. 2015. Effects of variation in wool fiber curvature and yarn hairiness on sensorial assessment of knitted fabrics. Text. Res. J. 85(11):1153-1166. doi: 10.1177/0040517514566112

Mortimer, S. 2009. Wool colour and fleece rot. In: Sheep production. The Australian wool education trust licensee for educational activities University of New England. Australian Wool Exchange Limited, Australia. 4:1-14. Available from: https://www.woolwise.com/wp-content/uploads/2017/07/Wool-412-512-08-T-04.pdf. (Accessed 18 May 2021.)

Mortimer, S. I., K. D. Atkins, S. J. Semple, and N. M. Fogarty. 2010. Predicted responses in Merino sheep from selection combining visually assessed and measured traits. Anim. Prod. Sci. 50:976-982. doi: https://doi.org/10.1071/AN10085

Mortimer, S. I., S. Hatcher, N. M. Fogarty, J. H. J. van der Werf, D. J. Brown, A. A. Swan, J. C. Greeff, G. Refshauge, J. E. Hocking Edwards, and G. M. Gaunt. 2017. Genetic parameters for wool traits, live weight, and ultrasound carcass traits in Merino sheep. J. Anim. Sci. 95:1879-1891. doi: 10.2527/jas2016.1234

Mrode, R. A. 2014. Linear models for the prediction of animal breeding values. 3rd ed. CABI Publishing, Wallingford, Oxfordshire, UK.

Nagy, I., J. Solkner, I. Komlosi, and L. Safar. 1999. Genetic parameters of production and fertility traits in Hungarian Merino sheep. J. Anim. Breed. Genet. 116:399-413. Available from: https://onlinelibrary.wiley.com/doi/pdf/10.1046/j.1439-0388.1999.00204.x?casa_token=vHe0PjK0aygAAAAA:P-7bdmyhcspbbvSOfItjNNERQmovfKuSBEukUDErbVDgF74xV29K2AVPHHtoSriDvfwZXV6W5QTVahfA (Accessed 25 May 2021.)

National Research Council (NRC). 2008. Changes in the sheep industry in the United States: Making the transition from tradition. National Academies Press. Washington, D.C. p. 247-258. doi: https://doi.org/10.17226/12245

Nielsen H. M. and P. R. Amer. 2007. An approach to derive economic weights in breeding objectives using partial profile choice experiments. Animal. 9:1254-1262. doi: https://doi.org/10.1017/S1751731107000729

Nolan, E., T. Farrell, M. Ryan, C. Gibbon, and F. Z. Ahmadi-Esfahani. 2013. Valuing quality attributes of Australian merino wool. Aust. J. Agric. Resour. Econ. 58:314-335. doi: https://doi.org/10.1111/1467-8489.12027

Notter, D. R. and J. D. Hough. 1997. Genetic parameter estimates for growth and fleece characteristics in Targhee sheep. J. Anim. Sci. 75:1729–1737. doi: https://doi.org/10.2527/1997.7571729x

Notter, D. R. 1998. The U.S. National Sheep Improvement Program: Across-flock genetic evaluations and new trait development. J. Anim. Sci. 76:(9)2324–2330. doi: https://doi.org/10.2527/1998.7692324x

Notter, D. R., L. A. Kuehn, and R. W. Kott. 2007. Genetic analysis of fibre characteristics in adult Targhee ewes and their relationship to breeding value estimates derived from yearling fleeces. Small Ruminant Research. 67:164–172. doi: https://doi.org/10.1016/j.smallrumres.200 5.09.015

Oldenbroek, K. and L. Van der Waaij. 2015. Animal breeding and genetics for BSc students. Centre for Genetic Resources, The Netherlands and Animal Breeding and Genomics Centre. p. 22–25. Available from: https://research.wur.nl/en/publications/textbook-animal-breeding-animal-breeding-and-genetics-for-bsc-stu (Accessed 15 January 2020.)

Pearson, R. E. 1982. Economic aspects of the choice of a breeding objective. Proc. 2nd World Congr. Genet. Appl. Livest. Prod. Madrid, Spain. 6:50-59. Available from: http://www.wcgalp.org/system/files/proceedings/1982/economic-aspects-choice-breeding-objective.pdf (Accessed 15 October 2019.)

Peterson, A. D., A. Brims, M. A. Brims, and S. G. Gherardi. 1998. Measuring the diameter profile of single wool fibres by using the single fiber analyser (SIFAN). J. Text. Inst. 89(3):441-448. doi 10.1080/00405009808658630

Ponzoni, R. W. 1988. The derivation of economic values combining income and expense in different ways: an example with Australian Merino sheep. J. Anim. Breed. Genet. 105:143-153. doi: https://doi.org/10.1111/j.1439-0388.1988.tb00284.x

Ponzoni, R. W., R. J. Grimson, K. S. Jaensch, D. H. Smith, D. R. Gifford, P. M. C. Ancell, J. R. W. Walkley, and P. I. Hynd. 1995. The Turretfield sheep breeding project: messages on phenotypic and genetic parameters for South Australian Merino sheep. Proc. Aust. Assoc. Anim. Breed. Genet. 11:303-313. Available from: http://www.aaabg.org/livestocklibrary/1995/ab95064.pdf (Accessed 20 May 2021.)

Purvis, I. W. and A. Swan. 1997. Can follicle density be used to enhance the rate of genetic improvement in Merino flocks? Proc. Assn. Adv. Anim. Breed. Genet. 12:512-515. Available from: https://www.researchgate.net/publication/268349288_Can_follicle_density_be_used_to_enhance_the_rate_of_genetic_improvement_in_Merino_flocks (Accessed 02 May 2021.)

Qi, K., C. J. Lupton, F. A. Pfeiffer, and D. L. Minikhiem. 1994. Evaluation of the Optical Fibre Diameter Analyzer for measuring fiber diameter parameters of sheep and goats. J. Anim. Sci. 72:1675-1679. doi: https://doi.org/10.2527/1994.7271675x

Reis, P. J. 1979. Effects of amino acids on the growth and properties of wool. In: Black, J. L., Reis, J., Eds., Physiological and environmental limitations to wool growth. University of New England Publishing Unit, Armidale, New South Wales. p. 223–242.

Riley, D. G., J. W. Thorne, R. R. Redden, A. D. Herring, and D. F. Waldron. 2020. Comparative performance of Dorper and Rambouillet ewes on West Texas range. Small Rumin. Res. 185:106065. doi: https://doi.org/10.1016/j.smallrumres.2020.106065

Rogers, G. E. and A. C. Schlink. Wool growth and production. In: D. J. Cottle, Ed., Int. Sheep and Wool Handbook. Nottingham University Press, Nottingham, UK. p. 373- 395.

Roldan, D. L., A. M. Dodero, F. Bidinost, H. R. Taddeo, D. Allain, M. A. Poli, and J. M. Elsen. 2010. Merino sheep: a further look at quantitative trait loci for wool production. Animal. 4(8):1330-1340. doi: 10.1017/S1751731110000315

Rose, M. and P. M. Pepper. 1999. Genetic Parameters for Production Traits in Queensland Merinos. AAABG. Proc. 13th Assn. Adv. Anim. Breed. Genet. 13:114-117. Available from: https://core.ac.uk/reader/77131530 (Accessed 12 July 2021).

Safari, A. and N. M. Fogarty. 2003. Genetic parameters for sheep production traits: estimates from literature. Tech. Bull. 49. NSW Agric., Orange, Australia. Available from: https://ksu-illiad-oclc-org.er.lib.k-state.edu/illiad/illiad.dll?Action=10&Form=75&Value=1036937 (Accessed 13 September 2021.)

Safari, E., N. M. Fogarty, and A. R. Gilmour. 2005. A review of genetic parameter estimates for wool growth, meat and reproduction traits in sheep. Livest. Prod. Sci. 92:271-289. doi: https://doi.org/10.1016/j.livprodsci.2004.09.003

Safari, E., N. M. Fogarty, A. R. Gilmour, K. D. Atkins, S. I. Mortimer, A. A. Swan, F. D. Brien, J. C. Greeff, and J. H. J. van der Werf. 2007a. Across population genetic parameters for wool, growth and reproduction traits in Australian Merino sheep. 2. Estimates of heritability and variance components. Aust. J. Agri. Res. 58:177-184. doi: https://doi.org/10.1071/AR06162

Safari, E., N. M. Fogarty, A. R. Gilmour, K. D. Atkins, S. I. Mortimer, A. A. Swan, F. D. Brien, J. C. Greeff, and J. H. J. Van der Werf. 2007b. Genetic correlations among and between wool, growth and reproduction traits in Merino sheep. J. Anim. Breed. Genet. 124:65-72. doi: https://doi.org/10.1111/j.1439-0388.2007.00641.x

Schneeberger, M., S. A. Barwick, G. H. Crow, and K. Hammond. 1992. Economic indices using breeding values predicted by BLUP. J. Anim. Breed. Genet. 109:180-187. doi: https://doi.org/10.1111/j.1439-0388.1992.tb00395.x

Schoenian, S. 2020. Wool marketing. In: Sheep 201, A beginner's guide to raising sheep. University of Maryland. Available from: http://www.sheep101.info/201/woolmarketing.html (Accessed 15 March 2021.)

Searle, S. R. 1961. Phenotypic, genetic, and environmental correlations. Biometrics. 17(3):474-480. doi: 129.130.19.169

Sherlock, R. G., N. Lopez-Villalobos, and D. J. Garrick. 2003. Genetic parameters for wool traits in ultra-fine New Zealand Merinos. Proc. Assoc. Adv. Anim. Breed. Genet. 15:277-280. Available from: https://www.researchgate.net/profile/Dorian-Garrick/publication/267381782_Genetic_parameters_for_wool_traits_in_ultra-fine_New_Zealand_Merinos/links/5460b58f0cf27487b4523dd9/Genetic-parameters-for-wool-traits-in-ultra-fine-New-Zealand-Merinos.pdf (Accessed 10 April 2021.)

Shultz, F. T. 1986. Formulation of breeding objectives for poultry meat production. Proc. 3rd World Congr. Genet. Appl. Livest. Prod., Lincoln, NE XU:215. Available from: https://ksu-illiad-oclc-org.er.lib.k-state.edu/illiad/illiad.dll?Action=10&Form=75&Value=1036948 (Accessed 25 October 2019.)

Simm, G., R. M. Lewis, B. Grundy, and W. S. Dingwall. 2002. Responses to selection for lean growth in sheep. Anim. Sci. 74:39-50. doi: https://doi.org/10.1017/S135772980005219X

Simpson, W. S. and G. H. Crawshaw. 2002. Wool: Science and Technology. Woodhead Publishing, Cambridge, England. p. 1-20. Available from: https://app.knovel.com/web/toc.v/cid:kpWST00001/viewerType:toc/ (Accessed 15 April 2021.)

Sommerville, P. J. 2002. Wool metrology: Past and current trends and future requirements. Wool Tech. Sheep Breed. 50:853-860. Available from: https://sheepjournal.net/index.php/WTSB/article/view/1652/1642 (Accessed 07 June 2021.)

Sommerville, P. 2007. Fundamental principles of fibre fineness measurement. AWTA Ltd. Melbourne, Australia. Available from: http://www.woolwise.com/wp-content/uploads/2017/06/Fibre_Fineness_Measurement_Fundamentals.pdf. (Accessed 26 April 2021.)

Steeneveld, W., J. Swinkels, and H. Hogeveen. 2007. Stochastic modelling to assess economic effects of treatment of chronic subclinical mastitis caused by Streptococcus uberis. J. Dairy Sci. 74:459-567. doi: 10.1017/S0022029907002828

Steere, T. 2009. Sampling techniques. In: Wool biology and metrology. The Australian wool education trust licensee for educational activities University of New England. Australian Wool Exchange Limited, Australia. 9:1-10. Available from:

https://www.woolwise.com/wp-content/uploads/2017/07/Wool-472-572-08-T-07.pdf (Accessed 19 May 2021.)

Stobart, R. H., W. C. Russell, S. A. Larsen, C. L. Johnson, and J. L. Kinnison. 1986. Sources of variation in wool fiber diameter. J. Anim. Sci. 62:1181-1186. doi: https://doi.org/10.2527/jas1986.6251181x

Swan, A. A., J. Lax, and I. W. Purvis. 1995. Genetic variation in objectively measured wool traits in CSIRO's fine wool flock. Proc. Aust. Assn. Anim. Breed. Genet. 11:516-520. Available from: http://www.aaabg.org/proceedings/1995/ab95103.pdf (Accessed 05 May 2021.)

Swan, A. A., I. W. Purvis, and L. R. Piper. 2008. Genetic parameters for yearling wool production, wool quality and body weight traits in fine wool Merino sheep. Aust. J. Exp. Agric. 48:1168-1176. doi: https://doi.org/10.1071/EA07425

Taylor, P. J., K. D. Atkins, and A. R. Gilmour. 1999. Genetic association between fibre curvature, staple crimp and wool production and quality of merino sheep. Proc. Assoc. Anim. Breed. Genet. 13:456-459. Available from: http://www.aaabg.org/livestocklibrary/1999/AB99108.pdf (Accessed 25 March 2022.)

Technology Innovation Agency (TIA). 2016. Annual report 2015/2016. Department: Science and Technology, Republic of South Africa. p. 1-188. Available from: https://www.tia.org.za/core/uploads/2017/12/TIA-Annual-Report-2016.pdf (Accessed 4 May 2021.)

Terrill, C. E. and L. N. Hazel. 1945. Heritability of weaning weight and staple length in range Rambouillet lambs. J. Anim. Sci. 4:347-358. doi: https://doi.org/10.2527/jas1945.44347x

Textile exchange. 2020. Preferred fibre market report. Available from: https://textileexchange.org/wp-content/uploads/2020/06/Textile-Exchange_Preferred-Fiber-Material-Market-Report_2020.pdf (Accessed 15 March 2021.)

Thornberry, K. J. and K. D. Atkins. 1984. Variation in non-wool components of the greasy fleece over the body of Merino sheep. Aust. J. Exp. Agric. Anim. Husb. 24:72-76. doi: https://doi.org/10.1071/EA9840062

USDA-ERS. 2020. U.S. supply and use estimates and prices. Available from: https://www.ers.usda.gov/webdocs/DataFiles/48516/U.S.WoolSupplyandDemand.xlsx?v=5600.8 (Accessed 14 March 2021.)

USDA-NASS. 1996. Wool and mohair. Washington, D.C. 3-96. Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/1r66j1131/rx913s416/mg74qq056/WoolMoha-03-27-1996.pdf (Accessed 14 March 2021.)

USDA-NASS. 2021a. Quick Stats: Wool. Available from: https://quickstats.nass.usda.gov/results/902E6DFA-841F-3884-8286-FA72C71316B7. (Accessed 18 April 2021.)

USDA-NASS. 2021b. Sheep and goats. Fort Collins, CO. N1949.1611 Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/000000018/41688945h/f47539332/shep0121.pdf (Accessed 10 February 2021.)

USDA-SRS. 1976. Wool and mohair. Washington, D.C. 20250. Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/1r66j1131/0p096938f/6w924f38h/WoolMoha-04-02-1976.pdf (Accessed 9 April 2021.)

United States International Trade Commission (USITC). 1998. Industry and Trade Summary: Wool and Related Animal Hair. Available from: https://www.usitc.gov/publications/332/PUB3145.pdf (Accessed 15 February 2022.)

Valera, M., F. Arrebola, M. Juarez, and A. Molina. 2009. Genetic improvement of wool production in Spanish Merino sheep: genetic parameters and simulation of selection strategies. Anim. Prod. Sci. 49:43-47. doi: https://doi.org/10.1071/EA07061

Vandepitte, W.M. and L. N. Hazel. 1977. The effect of errors in economic weights on the accuracy of selection indexes. Ann. Genet. Sel. Anim. 9:87-103. doi: https://doi.org/10.1186/1297-9686-9-1-87

Walker, J. W., W. C. Stewart, R. Pope, S. L. Spear, M. Ebert, and T. W. Murphy. 2018. Evaluation of mean fiber diameter measurements by FibreLux micron meter and OFDA2000 in Texas and Intermountain west wool. Small Rumin. Res. 159:31-37. doi: https://doi.org/10.1016/j.smallrumres.2017.12.008

Walker, J. W., R. Pope, and F. A. Pfeiffer. 2021. On-farm testing of FibreLux Micron Meter and OFDA2000 compared to Sirolan Laserscan in the laboratory. Small Rumin. Res. 200:106401. doi: https://doi.org/10.1016/j.smallrumres.2021.106401

Walsh, B. and M. Lynch. 2000. Theory of index selection. In: Evolution and Selection of Quantitative Traits. Sinauer Assoc. Inc., Sunderland, MA. p. 434. Available from: http://nitro.biosci.arizona.edu/zdownload/Volume2/Chapter23.pdf. Accessed August 24, 2020.

Wang, C. T. and G. E. Dickerson. 1991. A deterministic computer simulation model of life-cycle lamb and wool production. J. Anim. Sci. 69:4312-4323. doi: https://doi.org/10.2527/1991.69114312x

Wang, H., T. Mahar, X. Liu, and X. Wang. 2007. Measurement precision and evaluation of the diameter profiles of single wool fibers. Text. Res. J. 77(12):981-991. doi:10.1177/0040517507083555

Whitney, T. R., D. F. Waldron, and T. D. Willingham. 2009. Evaluating nutritional status of Dorper and Rambouillet ewes in range sheep production. Sh. G. Res. J. 24:10-16. Available from: https://www.researchgate.net/profile/Travis-Whitney-2/publication/228640673_Evaluating_nutritional_status_of_Dorper_and_Rambouillet_ewes_in_range_sheep_production/links/00b7d51df1e6c6bad8000000/Evaluating-nutritional-status-of-Dorper-and-Rambouillet-ewes-in-range-sheep-production.pdf (Accessed 12 December 2020.)

Wilson, D. E. and D. G. Morrical. 1991. The national sheep improvement program: a review. J. Anim. Sci. 69:3 872-3881. doi: https://doi.org/10.2527/1991.6993872x

Wilton, J. W. and L. D. Van Vleck. 1968. Selection of dairy cows for economic merit. J. Dairy Sci. 51(10):1680-1688. doi: 10.3168/jds.S0022-0302(68)87252-2

Wood, E. 2003. Textile properties of wool and other fibres. Wool Tech. and Sheep Breed. 51(3):272-290. Available from: https://www.sheepjournal.net/index.php/WTSB/article/view/1711/1699 (Accessed 03 March 2021.)

Wuliji, T., K. G. Dodds, J. T. J. Land, R. N. Andrews, and P. R. Turner. 2001. Selection for ultrafine Merino sheep in New Zealand: heritability, phenotypic and genetic correlations of live weight, fleece weight and wool characteristics in yearlings. Anim. Sci. 72:241-250. doi: https://doi.org/10.1017/S1357729800055739

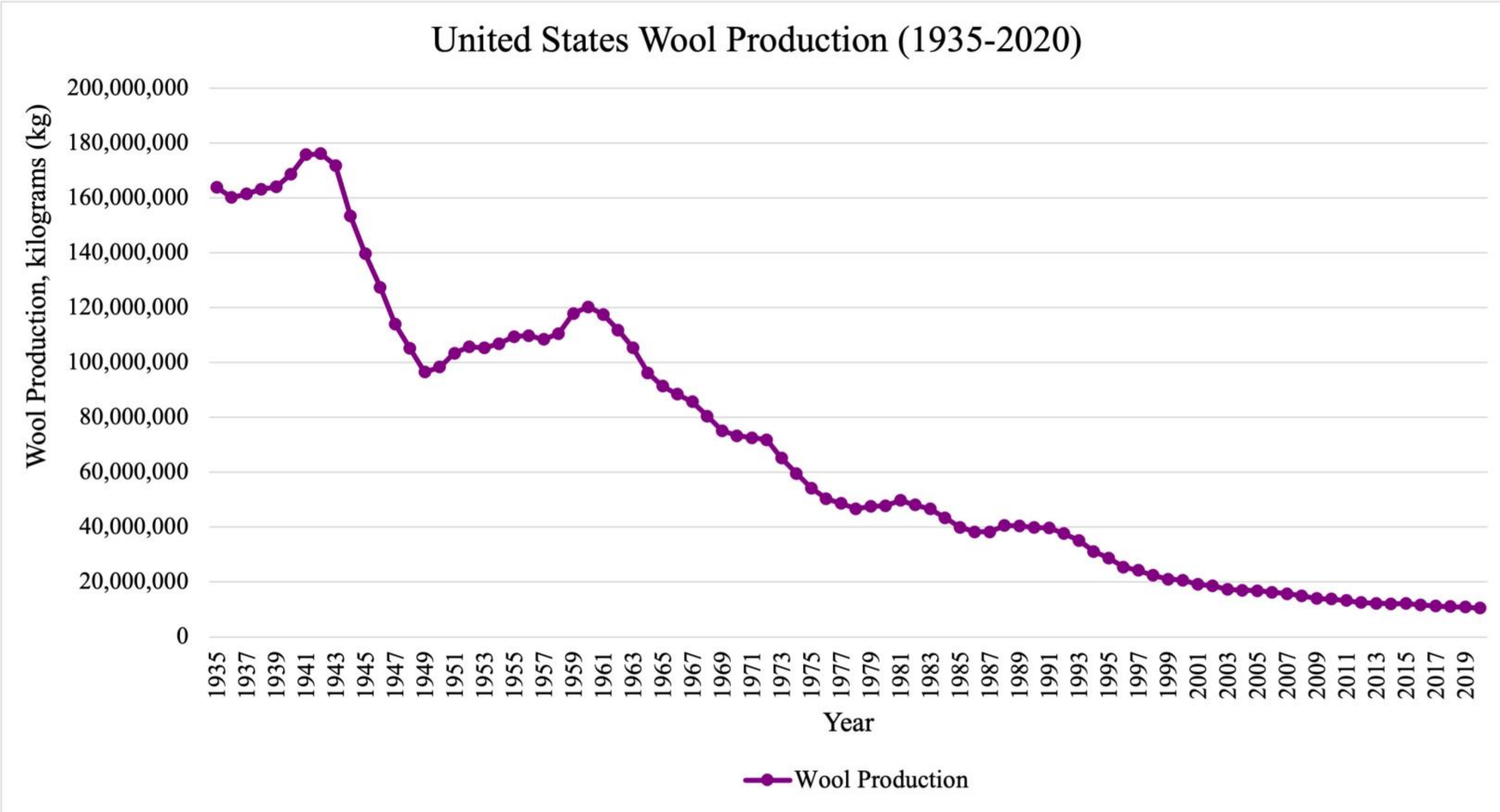

Figure 1.1 Decline in United States wool production from 1935 to 2020 based on total kilograms produced (USDA-NASS, 2021a).

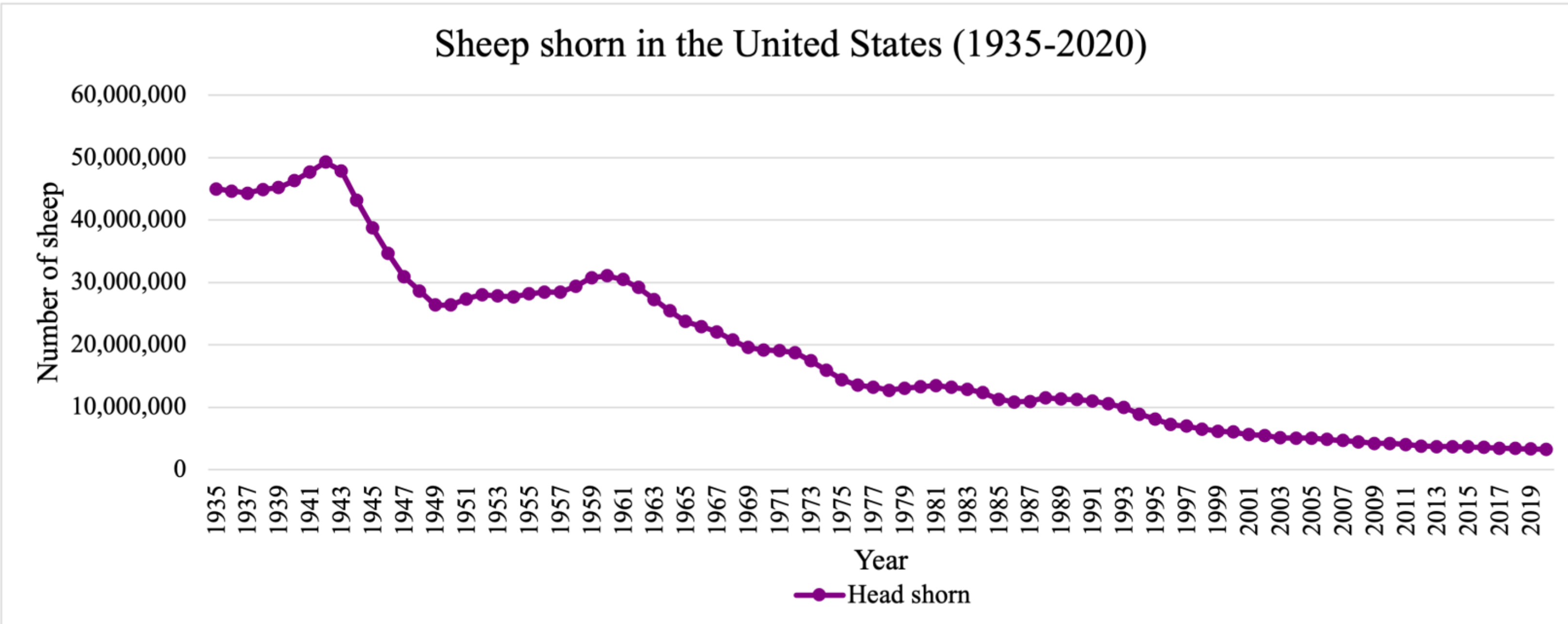

Figure 1.2 Decline in United States number of sheep shorn from 1935 to 2020 (USDA-NASS, 2021a).

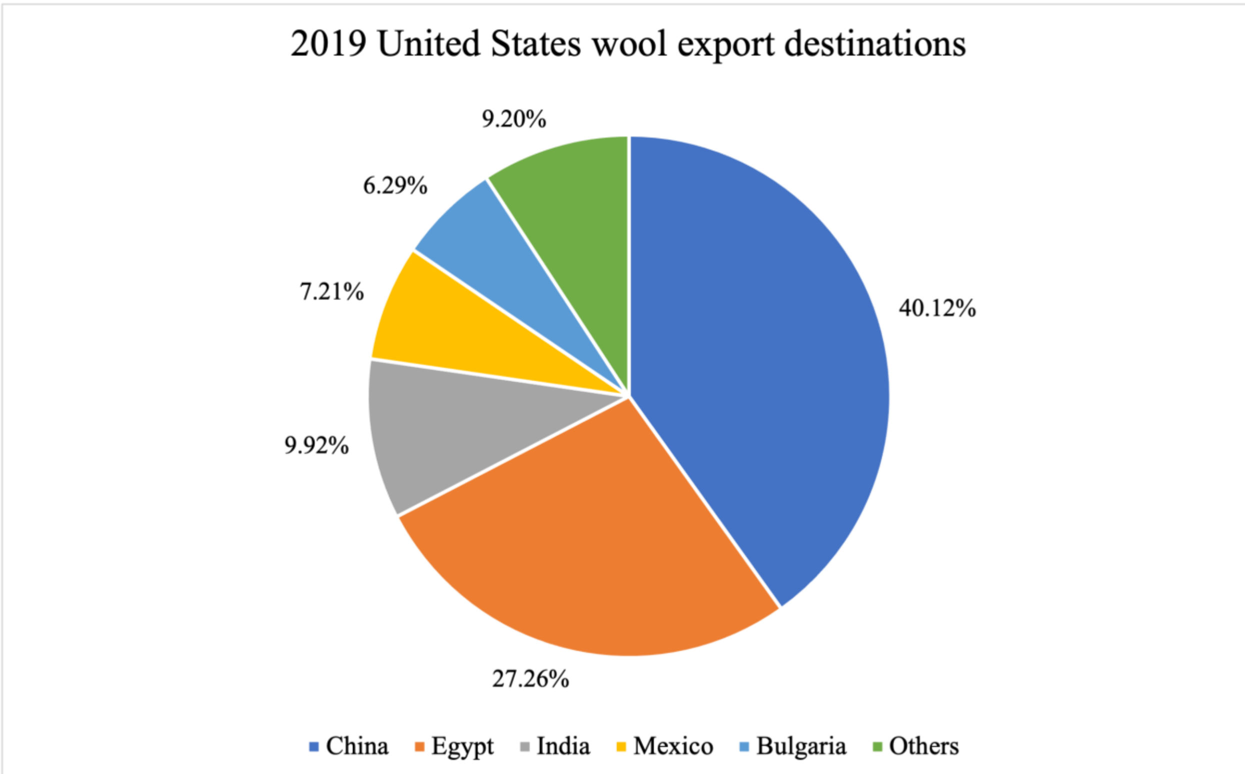

Figure 1.3 2019 United States wool export destinations (USDA-ERS, 2020).

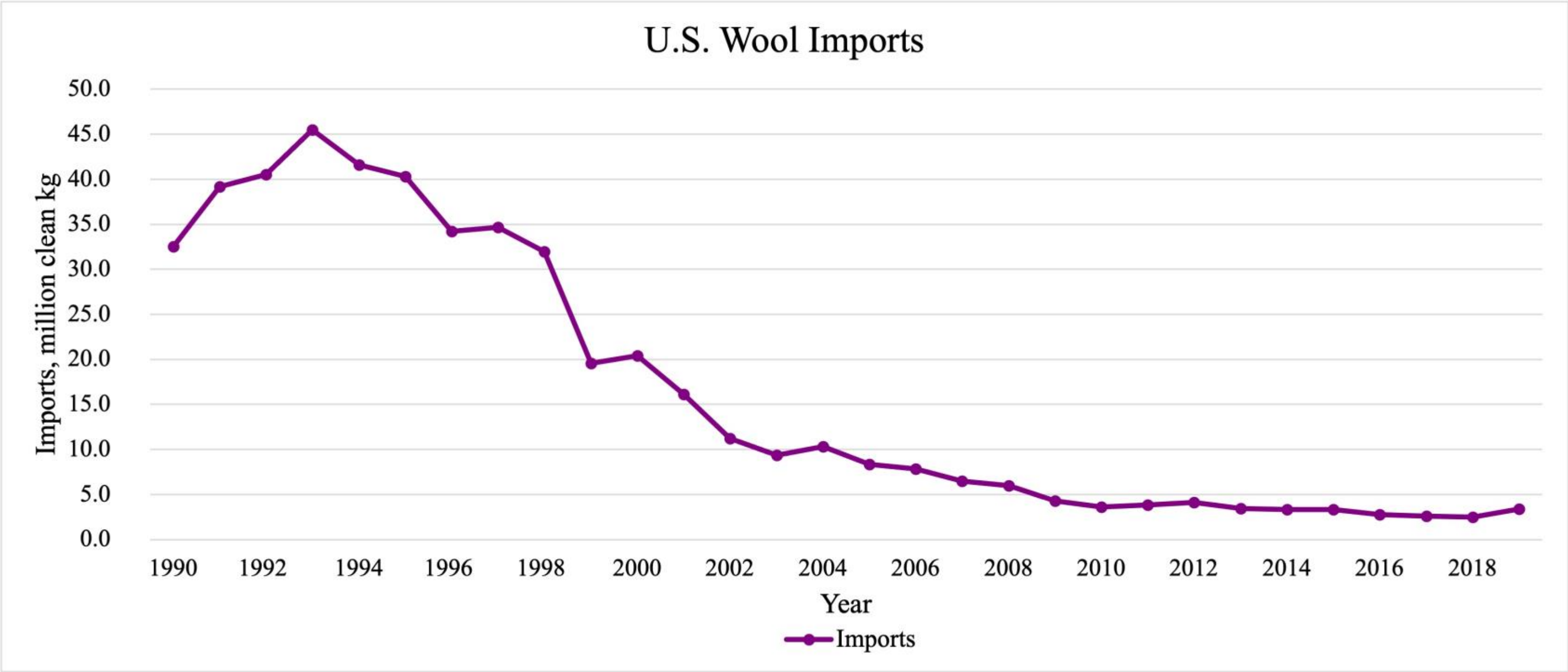

Figure 1.4 United States wool imports from 1990 to 2019 (USDA-ERS, 2020).

Table 1.1 The American, English, and Micron grading systems (Kott, 1993).

Wool Type	American Blood Grade	English/Spinning Count Grade	Micron Range (µm)
Fine	Fine	Finer than 80s	Under 17.70 µm
Fine	Fine	80s	17.70-19.14 µm
Fine	Fine	70s	19.15-20.59 µm
Fine	Fine	64s	20.60-22.04 µm
Medium	1/2 Blood	62s	22.05-23.49 µm
Medium	1/2 Blood	60s	23.50-24.94 µm
Medium	3/8 Blood	58s	24.95-26.39 µm
Medium	3/8 Blood	56s	26.40-27.84 µm
Medium	1/4 Blood	54s	27.85-29.29 µm
Medium	1/4 Blood	50s	29.30-30.99 µm
Coarse	Low 1/4 Blood	48s	31.00-32.69 µm
Coarse	Low 1/4 Blood	46s	32.70-34.39 µm
Coarse	Common	44s	34.40-36.19 µm
Very Coarse	Braid	40s	36.20-38.09 µm
Very Coarse	Braid	36s	38.10-40.20 µm
Very Coarse	Braid	Coarser than 36s	Over 40.20 µm

Table 1.2 Heritability estimates of wool production traits

Trait	Estimate	Standard Error	n	Breed	Source
Staple Length	0.17	0.01	25,990	Merino	Nagy et al. (1999)
	0.31	*	1,681	Targhee	Borg et al. (2009)
	0.40	*	--	Merino	Atkins (1997)
	0.42	*	5,000	Targhee	Borg et al. (2007)
	0.43	*	847	Targhee	Notter et al. (2007)
	0.46	0.04	15_b	Merino	Safari et al. (2005)
	0.65	0.04	3,341	Targhee	Hanford et al. (2003)
	0.75	0.26	371	Merino	Brown et al. (2002a)
Grease Fleece Weight	0.12	0.02	33,163	Merino	Nagy et al. (1999)
	0.32	*	3,473	Targhee	Notter and Hough (1997)
	0.32	*	2,314	Targhee	Borg et al. (2009)
	0.36	*	--	Merino	Atkins (1997)
	0.37	0.02	20_b	Merino	Safari et al. (2005)
	0.40	0.03	9,263	Merino	Swan et al. (2008)
	0.54	0.01	36,807	Targhee	Hanford et al. (2003)
	0.58	*	2200	Merino	Ponzoni (1995)
Clean Fleece Weight	0.20	0.11	1,785	Merino	Rose and Pepper (1999)
	0.34	*	--	Merino	Atkins (1997)
	0.36	0.02	30_b	Merino	Safari et al. (2005)
	0.37	0.04	5,055	Merino	Swan et al. (2008)
	0.59	*	2,200	Merino	Ponzoni et al. (1995)

* Indicates no reported standard error

$_b$ Indicates number of literature estimates used for a weighted average heritability estimate

Table 1.3 Heritability estimates of wool quality traits

Trait	Estimate	Standard Error	n	Breed	Source
Fiber Diameter	0.08	0.05	1,869	Merino	Valera et al. (2009)
	0.19	0.01	25,990	Merino	Nagy et al. (1999)
	0.25a	*	2,171	Targhee	Borg et al. (2009)
	0.41a	0.01	36,807	Targhee	Hanford et al. (2003)
	0.57	*	5,000	Targhee	Borg et al. (2007)
	0.58	*	2,083	Targhee	Notter and Hough (1997)
	0.64a	*	847	Targhee	Notter et al. (2007)
	0.66	0.02	9,249	Merino	Swan et. (2008)
	0.76	0.02	1,199	Merino	Cloete et al. (2003)
Yield	0.34	0.02	1,100	Merino	Sherlock et al. (2003)
	0.41	0.08	1,284	Merino	Brash et al. (1997)
	0.47	0.01	116,526	Merino	Safari et al. (2007a)
	0.50	*	--	Merino	Atkins (1997)
	0.56	0.03	15_b	Merino	Safari et al. (2005)
	0.60	0.03	5035	Merino	Swan et al. (2008)
	0.72	*	2,200	Merino	Ponzoni et al. (1995)
Fiber Diameter Coefficient of Variation	0.23	0.09	1,292	Merino	Lee et al. (2002)
	0.46	0.02	8,887	Merino	Swan et al. (2008)
	0.52	0.04	14_b	Merino	Safari et al. (2005)
	0.57	0.02	76,603	Merino	Safari et al. (2007a)
	0.74	0.02	1,199	Merino	Cloete et al. (2003)
Curvature	0.39	0.04	5,795	Merino	Mortimer et al. (2017)
	0.39	0.07	1,508	Merino	Taylor et al. (1999)
	0.42	0.07	2,876	Merino	Greef et al. (2008)
	0.47	0.02	26,636	Merino	Huisman et al. (2008)
	0.47	0.15	835	Merino	Brown et al. (2002a)

* Indicates no reported standard error

$_a$ Indicates heritability of spinning count

$_b$ Indicates the number of literature estimates used for a weighted average heritability estimate

Table 1.4 Heritability estimates of body weight traits

Trait	Estimate	Standard Error	n	Breed	Source
Birth Weight	0.18	0.01	73,140	Merino	Safari et al. (2007a)
	0.19	*	11,818	Targhee	Borg et al. (2009)
	0.21	0.03	8 [b]	Merino	Safari et al. (2005)
	0.22	0.04	9,135	Merino	Mortimer et al. (2017)
	0.25	0.02	33,994	Targhee	Hanford et al. (2003)
	0.39	0.07	5,139	Merino	Huisman et al. (2008)
Weaning Weight	0.10	*	5,000	Targhee	Borg et al. (2007)
	0.14	0.04	7,007	Merino	Mortimer et al. (2017)
	0.20	0.02	9,271	Merino	Swan et al. (2008)
	0.22	0.02	32,715	Targhee	Hanford et al. (2003)
	0.29	0.01	72,383	Merino	Safari et al. (2007a)
	0.72	0.03	36,805	Merino	Huisman et al. (2008)
Yearling Weight	0.26	*	1,237	Targhee	Notter and Hough (1997)
	0.26	*	5,000	Targhee	Borg et al. (2007)
	0.32	*	1,122	Targhee	Borg et al. (2009)
	0.38	0.07	5,304	Merino	Mortimer et al. (2017)
	0.43	0.02	65,829	Merino	Huisman et al. (2008)
	0.51	0.04	7,697	Merino	Swan et al. (2008)

* Indicates no reported standard error

[b] Indicates the number of literature estimates used for a weighted average heritability estimate

Table 1.5 Genetic and Phenotypic correlations of wool and body weight traits

Genetic correlation	Phenotypic correlation	n	Breed	Source
	Fiber Diameter and Staple Length			
-0.69 ± unpublished*	--	3,341	Targhee	Hanford et al. (2003)
-0.54 ± unpublished*	--	7,080	Rambouillet	Bromley et al. (2000)
-0.53 ± unpublished*	--	5,534	Targhee	Bromley et a. (2000)
0.13 ± 0.04	0.16 ± 0.02	5,061	Merino	Swan et al. (2008)
0.16 ± 0.01	0.29 ± 0.05	9,799	Merino	Huisman and Brown (2009)
0.10 ± unpublish	--	--	--	Lupton (2015)
0.19 ± 0.14	0.19 ± 0.09	--	Merino	Safari et al. (2005)
	Fiber Diameter and Grease Fleece Weight			
0.59 ± 0.09-0.38	0.32 ± 0.02-0.06	635	Merino	Brown et al. (2002b)
0.36 ± 0.13	0.31 ± 0.08	--	Various	Safari et al. (2005)
0.27 ± 0.02	0.24 ± 0.01	116,025	Merino	Safari et al. (2007b)
0.26 ± unpublished	--	--	--	Lupton (2015)
0.07 ± 0.03	--	25,990	Merino	Nagy et al. (1999)
--	0.06 ± unpublished	690	Merino	Beattie (1961)
0.25 ± 0.05	0.29 ± 0.01	9,249	Merino	Swan et al. (2008)
0.57 ± unpublished	0.10 ± unpublished	5,000	Targhee	Borg et al. (2007)
0.51 ± unpublished	--	2,083	Targhee	Notter and Hough (1997)
-0.47 ± unpublished*	--	36,807	Targhee	Hanford et al. (2003)
-0.46 ± unpublished*	--	18,443	Rambouillet	Bromley et al. (2000)
-0.50 ± unpublished*	--	15,014	Targhee	Bromley et al. (2000)
	Fiber Diameter and Clean Fleece Weight			
0.15 ± 0.06	0.22 ± 0.02	5,055	Merino	Swan et al. (2008)
0.38 ± 0.14	0.15 ± 0.03	1,284	Merino	Brash et al. (1997)
0.29 ± 0.02	0.24 ± 0.01	115,244	Merino	Safari et al. (2007b)
0.28 ± 0.11	0.25 ± 0.10	--	Various	Safari et al. (2005)
0.32 ± 0.14	0.12 ± 0.03	1,292	Merino	Lee et al. (2002)
0.43 ± 0.03	0.26 ± 0.01	87,140	Merino	Huisman and Brown (2009)
	Fiber Diameter and Yield			

0.06 ± 0.02	0.00 ± 0.01	116,025	Merino	Safari et al. (2007b)
0.04 ± unpublished	--	--	--	Lupton (2015)
0.04 ± 0.10	0.01 ± 0.10	--	various	Safari et al. (2005)
-0.01 ± 0.04	0.00 ± 0.02	5,035	Merino	Swan et al. (2008)
Fiber Diameter and Fiber Diameter Coefficient of Variation				
-0.18 ± 0.04	-0.13 ± 0.01	8,887	Merino	Swan et al. (2008)
-0.16 ± 0.02	-0.10 ± 0.01	76,603	Merino	Safari et al. (2007b)
-0.16 ± 0.03	-0.15 ± 0.01	71,143	Merino	Huisman and Brown (2009)
-0.10 ± 0.12	-0.09 ± 0.12	--	Merino	Safari et al. (2005)
Fiber Diameter and Curvature				
-0.15 ± 0.01	-0.31 ± 0.03	26,636	Merino	Huisman and Brown (2009)
-0.02 ± 0.09-0.38	-0.33 ± 0.02-0.06	635	Merino	Brown et al. (2002b)
-0.20 ± 0.08	-0.02 ± 0.01-0.03	1,508	Merino	Taylor et al. (1999)
Fiber Diameter and Birth Weight				
-0.04 ± unpublished*	--	9,321	Targhee	Bromley et al. (2000)
-0.23 ± unpublished*	--	9,530	Rambouillet	Bromley et al. (2000)
-0.06 ± unpublished*	--	33,994	Targhee	Hanford et al. (2003)
-0.15 ± 0.02	-0.06 ± 0.01	73,140	Merino	Safari et al. (2007b)
-0.07 ± unpublished	-0.04 ± unpublished	2,198	Merino	Di et al. (2011)
Fiber Diameter and Weaning Weight				
0.05 ± 0.19	0.05 ± 0.07	--	Various	Safari et al. (2005)
-0.04 ± unpublished	0.08 ± unpublished	2,198	Merino	Di et al. (2011)
0.05 ± 0.03	0.07 ± 0.01	72,338	Merino	Safari et al. (2007b)
0.00 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
0.19 ± 0.06	0.14 ± 0.02	9,249	Merino	Swan et al. (2008)
Fiber Diameter and Yearling Weight				
0.21 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
0.20 ± 0.05	0.24 ± 0.02	7,697	Merino	Swan et al. (2008)
0.17 ± 0.04	0.07 ± 0.01	28,261	Merino	Safari et al. (2007b)
0.03 ± unpublished	0.07 ± unpublished	2,198	Merino	Di et al. (2011)
Staple Length and Grease Fleece Weight				
0.56 ± unpublished	--	7,080	Rambouillet	Bromley et al. (2000)

0.50 ± unpublished	--	5,534	Targhee	Bromley et al. (2000)
0.44 ± 0.22	0.32 ± 0.08	--	Various	Safari et al. (2005)
0.29 ± 0.07	0.28 ± 0.02	5,061	Merino	Swan et al. (2008)
0.27 ± 0.02	0.42 ± 0.06	9,799	Merino	Huisman and Brown (2009)
0.54 ± unpublished	--	3,341	Targhee	Hanford et al. (2003)
0.44 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
		Staple Length and Clean Fleece Weight		
0.44 ± unpublished	0.34 ± unpublished	5,100	Merino	Purvis and Swan (1997)
0.21 ± 0.14	0.30 ± 0.04	579	Merino	Wuliji et al. (2001)
0.36 ± 0.17	0.33 ± 0.08	--	Various	Safari et al. (2005)
0.38 ± 0.07	0.37 ± 0.02	5,055	Merino	Swan et al. (2008)
0.28 ± unpublished	0.36 ± unpublished	2,535	Merino	Swan et al. (1995)
0.37 ± 0.01	0.52 ± 0.05	9,799	Merino	Huisman and Brown (2009)
		Staple Length and Yield		
0.25 ± 0.08	0.19 ± 0.07	--	Various	Safari et al. (2005)
0.42 ± unpublished	--	--	--	Lupton (2015)
0.29 ± 0.05	0.32 ± 0.01	5,035	Merino	Swan et al. (2008)
0.25 ± unpublished	0.25 ± unpublished	--	Merino	Atkins (1997)
		Staple Length and Fiber Diameter Coefficient of Variation		
-0.06 ± 0.13	-0.12 ± 0.02	--	Merino	Safari et al. (2005)
-0.09 ± 0.05	-0.13 ± 0.02	5,061	Merino	Swan et al. (2008)
-0.30 ± unpublished	-0.07 ± unpublished	2,190	Merino	Di et al. (2011)
-0.18 ± 0.01	-0.18 ± 0.06	9,799	Merino	Huisman and Brown (2009)
0.01 ± unpublished	0.09 ± unpublished	2,535	Merino	Swan et al. (1995)
--	-0.06 ± unpublished	9,761	Targhee	Notter et al. (2007)
		Staple Length and Curvature		
--	-0.44 ± unpublished	9,761	Targhee	Notter et al. (2007)
-0.38 ± 0.05	-0.25 ± 0.01	9,799	Merino	Huisman and Brown (2009)
0.26 ± 0.09-0.38	--	371	Merino	Brown et al. (2002b)
		Staple Length and Birth Weight		
0.10 ± unpublished	--	3,341	Targhee	Hanford et al. (2003)
0.26 ± unpublished	--	5,534	Targhee	Bromley et al. (2000)

0.27 ± unpublished	--	7,080	Rambouillet	Bromley et al. (2000)
0.50 ± unpublished	0.05 ± unpublished	3,309	Merino	Di et al. (2011)
Staple Length and Weaning Weight				
0.08 ± unpublished	--	3,341	Targhee	Hanford et al. (2003)
0.47 ± unpublished	0.20 ± unpublished	3,309	Merino	Di et al. (2011)
0.00 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
0.33 ± 0.08	0.10 ± 0.02	5,061	Merino	Swan et al. (2008)
Staple Length and Yearling Weight				
0.41 ± unpublished	0.20 ± unpublished	2,981	Merino	Di et al. (2011)
0.27 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
0.26 ± 0.07	0.19 ± 0.02	5,061	Merino	Swan et al. (2008)
Grease Fleece Weight and Clean Fleece Weight				
0.90 ± unpublished	0.94 ± unpublished	2,535	Merino	Swan et al. (1995)
0.65 ± 0.11	0.79 ± 0.01	1,785	Merino	Rose and Pepper (1999)
0.86 ± 0.07	0.90 ± 0.03	--	various	Safari et al. (2005)
0.84 ± 0.05	0.92 ± 0.01	1,785	Merino	Wuliji et al. (2001)
0.89 ± 0.01	0.79 ± 0.01	115,244	Merino	Safari et al. (2007b)
0.76 ± 0.01	0.78 ± 0.01	68,340	Merino	Huisman and Brown (2009)
0.90 ± 0.01	0.84 ± 0.02	5,055	Merino	Swan et al. (2008)
Grease Fleece Weight and Yield				
-0.18 ± 0.02	-0.07 ± 0.01	116,526	Merino	Safari et al. (2007b)
-0.15 ± 0.07	0.04 ± 0.02	5,035	Merino	Swan et al. (2008)
-0.14 ± 0.14	-0.04 ± 0.11	--	Various	Safari et al. (2005)
Clean Fleece Weight and Yield				
0.28 ± 0.02	0.35 ± 0.01	115,244	Merino	Safari et al. (2007b)
0.28 ± 0.07	0.37 ± 0.02	5,035	Merino	Swan et al. (2008)
0.38 ± 0.10	0.37 ± 0.12	--	Various	Safari et al. (2005)
Grease Fleece Weight and Fiber Diameter Coefficient of Variation				
0.06 ± 0.06	-0.09 ± 0.01	8,887	Merino	Swan et al. (2008)
0.10 ± 0.02	0.05 ± 0.01	76,603	Merino	Safari et al. (2007b)
0.09 ± 0.17	0.36 ± 0.10	--	various	Safari et al. (2005)
0.19 ± 0.03	0.01 ± 0.01	68,340	Merino	Huisman and Brown (2009)

		Clean Fleece Weight and Fiber Diameter Coefficient of Variation		
0.00 ± 0.07	-0.12 ± 0.02	5,055	Merino	Swan et al. (2008)
0.01 ± 0.02	0.01 ± 0.01	76,603	Merino	Safari et al. (2007b)
0.19 ± 0.10	-0.04 ± 0.09	--	various	Safari et al. (2005)
0.14 ± 0.04	-0.05 ± 0.01	69,496	Merino	Huisman and Brown (2009)
		Grease Fleece Weight and Curvature		
0.44 ± 0.09-0.38	-0.35 ± 0.02-0.06	664	Merino	Brown et al. (2002b)
-0.19 ± 0.01	-0.37 ± 0.05	26,636	Merino	Huisman and Brown (2009)
		Clean Fleece Weight and Curvature		
-0.25 ± 0.01	-0.51 ± 0.04	26,636	Merino	Huisman and Brown (2009)
-0.64 ± 0.08	-0.31 ± 0.01-0.03	1,508	Merino	Taylor et al. (1999)
		Grease Fleece Weight and Birth Weight		
0.13 ± 0.19	0.34 ± 0.03	1,801	Merino	Wuliji et al. (2001)
0.11 ± 0.03	0.18 ± 0.01	73,140	Merino	Safari et al. (2007b)
0.24 ± unpublished	--	33,994	Targhee	Hanford et al. (2003)
-0.08 ± unpublished	0.10 ± unpublished	2,969	Merino	Di et al. (2011)
0.21 ± 0.03	0.24 ± 0.11	--	Various	Safari et al. (2005)
		Clean Fleece Weight and Birth Weight		
0.18 ± 0.18	0.34 ± 0.03	1,785	Merino	Wuliji et al. (2001)
0.10 ± 0.03	0.20 ± 0.01	73,140	Merino	Safari et al. (2007b)
0.11 ± 0.07	0.24 ± 0.10	--	Various	Safari et al. (2005)
		Grease Fleece Weight and Weaning Weight		
0.24 ± unpublished	--	32,715	Targhee	Hanford et al. (2003)
0.25 ± 0.03	0.32 ± 0.01	72,338	Merino	Safari et al. (2007b)
0.49 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
0.33 ± 0.07	0.49 ± 0.02	9,263	Merino	Swan et al. (2008)
0.63 ± unpublished	0.28 ± unpublished	2,969	Merino	Di et al. (2011)
0.08 ± 0.18	0.48 ± 0.02	1,801	Merino	Wuliji et al. (2001)
0.24 ± 0.16	0.25 ± 0.09	--	Various	Safari et al. (2005)
		Clean Fleece Weight and Weaning Weight		
0.20 ± 0.03	0.32 ± 0.01	72,338	Merino	Safari et al. (2007b)
0.45 ± 0.07	0.50 ± 0.02	5,055	Merino	Swan et al. (2008)

0.13 ± 0.17	0.47 ± 0.02	1,785	Merino	Wuliji et al. (2001)
0.21 ± 0.16	0.31 ± 0.15	--	Various	Safari et al. (2005)
Grease Fleece Weight and Yearling Weight				
0.60 ± unpublished	--	5,000	Targhee	Borg et al. (2007)
0.26 ± 0.04	0.44 ± 0.01	28,261	Merino	Safari et al. (2007b)
0.25 ± 0.06	0.46 ± 0.02	7,697	Merino	Swan et al. (2008)
0.48 ± unpublished	0.39 ± unpublished	2,969	Merino	Di et al. (2011)
Clean Fleece Weight and Yearling Weight				
0.23 ± 0.04	0.43 ± 0.01	28,261	Merino	Safari et al. (2007b)
0.23 ± 0.08	0.42 ± 0.02	5,055	Merino	Swan et al. (2008)
Yield and Fiber Diameter Coefficient of Variation				
0.38 ± 0.14	-0.03 ± 0.03	1,284	Merino	Brash et al. (1997)
-0.08 ± 0.19	-0.13 ± 0.23	--	Various	Safari et al. (2005)
-0.14 ± 0.03	-0.10 ± 0.01	76,603	Merino	Safari et al. (2007b)
-0.21 ± 0.05	-0.17 ± 0.02	5,035	Merino	Swan et al. (2008)
-0.01 ± unpublished	-0.08 ± unpublished	2,535	Merino	Swan et al. (1995)
-0.05 ± unpublished	-0.05 ± unpublished	--	Merino	Atkins (1997)
Yield and Curvature				
-0.37 ± 0.13	-0.38 ± 0.02	--	Mixed	Hatcher and Atkins (2000)
--	-0.14 ± unpublished	585	Merino	Roldan et al. (2010)
Yield and Birth Weight				
-0.02 ± 0.03	0.06 ± 0.01	73,140	Merino	Safari et al. (2007b)
-0.25 ± 0.01	0.05 ± 0.02	--	Various	Safari et al. (2005)
Yield and Weaning Weight				
-0.04 ± 0.00	0.02 ± 0.01	72,338	Merino	Safari et al. (2007b)
0.09 ± 0.09	0.14 ± 0.02	5,035	Merino	Swan et al. (2008)
-0.07 ± 0.10	0.00 ± 0.02	--	Various	Safari et al. (2005)
Yield and Yearling Weight				
0.01 ± 0.03	0.04 ± 0.01	28,261	Merino	Safari et al. (2007b)
-0.00 ± 0.07	0.05 ± 0.02	5,035	Merino	Swan et al. (2008)
Fiber Diameter Coefficient of Variation and Curvature				
0.87 ± 0.09-0.38	0.04 ± 0.02-0.06	501	Merino	Brown et al. (2002b)

0.01 ± 0.01	0.01 ± 0.04	26,636	Merino	Huisman and Brown (2009)
--	-0.04 ± unpublished	5,000	Targhee	Notter et al. (2007)
Fiber Diameter Coefficient of Variation and Birth Weight				
0.34 ± unpublished	0.04 ± unpublished	2,190	Merino	Di et al. (2011)
0.16 ± 0.03	0.04 ± 0.01	73,140	Merino	Safari et al. (2007b)
0.49 ± 0.14	-0.09 ± 0.05	5,139	Merino	Huisman and Brown (2008)
Fiber Diameter Coefficient of Variation and Weaning Weight				
-0.12 ± 0.07	-0.15 ± 0.02	8,887	Merino	Swan et al. (2008)
-0.12 ± 0.02	-0.10 ± 0.01	72,338	Merino	Safari et al. (2007b)
-0.31 ± unpublished	-0.04 ± unpublished	2,190	Merino	Di et al. (2011)
-0.04 ± 0.05	-0.08 ± 0.02	36,805	Merino	Huisman and Brown (2008)
Fiber Diameter Coefficient of Variation and Yearling Weight				
-0.25 ± 0.05	-0.20 ± 0.01	7,697	Merino	Swan et al. (2008)
-0.35 ± unpublished	-0.01 ± unpublished	2,190	Merino	Di et al. (2011)
-0.37 ± 0.06	-0.21 ± 0.01	28,261	Merino	Safari et al. (2007b)
-0.07 ± 0.04	-0.08 ± 0.02	65,829	Merino	Huisman and Brown (2008)
Curvature and Birth Weight				
-0.05 ± 0.16	-0.04 ± 0.04	5,139	Merino	Huisman and Brown (2008)
--	0.18 ± unpublished	558	Merino	Roldan et al. (2010)
Curvature and Weaning Weight				
0.13 ± 0.06	0.04 ± 0.02	26,636	Merino	Huisman and Brown (2008)
--	-0.06 ± unpublished	556	Merino	Roldan et al. (2010)
Curvature and Yearling Weight				
-0.04 ± 0.05	-0.01 ± 0.01	26,636	Merino	Huisman and Brown (2008)

* Indicates correlations with spinning count

Chapter 2 - National wool production survey of sheep industry stakeholders

Introduction

According to the National Sheep Improvement Program (NSIP, 2019), the Fine Wool Consortium (FWC) was established in 2016 to improve fine wool sheep productivity and wool quality. To further that goal, they proposed the development of a multiple-trait genetic selection program, or selection index, focused on improving fine wool production (Notter and Lewis, 2018; NSIP, 2019). Improvement of wool quality has been a focus for the FWC as United States (U.S.) fine wool has been subject to considerable discounts compared to other countries, such as Australia. The development of a selection index could aid in the improvement of U.S. fine wool and potentially improve production and quality. Before index development can occur, however, selection criteria must be clearly defined through the development of breeding objectives (Hazel, 1943; MacNeil et al., 1997). Therefore, the aim of this research was to define a breeding objective to be used in fine wool index development through a fine wool industry survey.

Defining breeding objectives is the first step in developing a proper selection index and requires an understanding of economically relevant traits (ERT) and associated relative economic values (REV) to build an aggregate genotype (Pearson, 1982). The development of breeding objectives for sheep production can be complex, as genetic correlations between traits may be antagonistic, resulting in large, unfavorable correlated responses in other traits (Swan et al., 2008). Pearson (1982) argues when developing breeding objectives, traits should be selected based on whether they significantly impact the animal's profitability, so REV must be defined.

Methods of deriving REV for traits are either objective or non-objective (Just et al., 2018). Typically, selection indices are developed by objective methods such as bioeconomic modeling or data simulation of traits. These methods can be highly unpopular among producers, however, due to the lack of flexibility across different production systems and failure to consider varying preferences for traits (Bourdon, 1998). Santos et al. (2019) found that selection indices are more likely to be adopted when industry stakeholders are involved in the decision-making process and breeding objectives are aligned with producer preferences.

Non-objective approaches to determining REV and breeding objectives have become increasingly popular, due to increased involvement by producers. By allowing stakeholders to be involved through non-objective approaches, such as survey or choice models, industry associations can gain producer acceptance of breeding objectives when approval is low (Nielsen & Amer, 2007). Non-objective methods also allow industry leaders to incorporate traits into a breeding objective that may be influenced by aspects other than those of economic importance (i.e., prestige, cultural significance, or functionality) or traits with little data available (Byrne et al., 2012a). For instance, in the U.S. fine wool industry, traits such as clean fleece weight (CFW), fleece yield (YLD), and staple strength (SS) have little recorded production data but are vital to selection for improved wool production and quality. For these reasons, fine wool industry participants should be involved in defining breeding objectives and REV estimates (Gizaw et al., 2009). Non-objective approaches are typically applied through subjective and choice experiment methods.

Subjective methods tend to include estimates and values provided by industry experts, producers, or other stakeholders, while choice experiment methods more commonly employ survey techniques to accurately identify producer inclinations (Just et al., 2018). Many studies (Duguma et al., 2011; Byrne et al., 2012b; Fuerst-Waltl et al., 2016; and Just et al., 2018) indicate that choice experiments can successfully derive breeding objectives when traditional approaches are not practical. For example, Byrne et al. (2012b) observed that preference-based REV gave higher importance to lambing difficulty than the economic evaluation. These studies support the idea that preference-based approaches may offer a better understanding of the needs and functionality of breeding objectives that traditional methods do not. Additionally, choice experiments applied through survey techniques can generate significant data resources for the industries they are applied to.

With direction from the FWC, a team of researchers at Kansas State University conducted a fine wool industry survey to acquire information from the three main industry sectors: producers, marketers, and processors. The information obtained aided industry leaders in understanding trait preferences of participants across the U.S. wool industry, how those preferences related to global production standards, and how more efficient selection programs could be established. Furthermore, survey results provided a clearer picture of the traits driving the U.S. wool industry and informed future research. It was postulated that trait preferences from marketing, processing, and production sectors of the industry would differ based on divergent goals. Differing goals of each wool industry sector are due to the different supply chain endpoints, in which there may be different areas of trait emphasis for each. The objectives of the survey were to: 1) collect stakeholder's preferences of wool traits, 2) compare industry stakeholder’s preferences of wool traits across the three U.S. wool industry sectors, and 3) utilize stakeholder preferences in a preliminary definition of a unified industry breeding objective to be used in the development of future genetic selection programs.

Materials & Methods

Survey design

This survey was designed utilizing the Qualtrics (Qualtrics®XM, Provo, UT) online survey tool and was reviewed by the Kansas State University Institutional Review Board but was exempt from a full review. Survey questions were strategically designed to capture general industry statistics and wool trait preferences of stakeholders across various sectors of the American wool industry. Data collected were general demographics, wool trait preferences, attitudes toward utilization of estimated breeding values (EBV), and genetic selection methods. The complete survey included 115 questions total, however, the number of questions presented to participants varied based on responses to prior questions. The survey completion time was projected to be approximately 15 to 20 min, with the option to pause and resume at any time.

The survey was initiated with demographic questions, followed by a series of questions stratified into the main U.S. fine wool sheep industry sectors: wool processing and wool marketing, with the production sector further divided into purebred/seedstock production, commercial production. Using Qualtrics display logic and survey flow options, participants were allocated to the appropriate industry sector. Multiple answer selections were allowed, therefore enabling participants to respond to multiple industry sector survey sections. Within the purebred/seedstock and commercial production divisions, additional responses further divided participants based on the type of production (maternal, terminal, or wool production focus) and if participants utilized EBV in their operation. To better evaluate the research objectives, respondents within each industry sector were asked multiple question sets regarding the preferential ranking of various selection criteria, opinions on selection and management, and preference of traits to be included in a fine wool sheep production index.

After being asked the demographic question block, regardless of selected industry sector (producer, marketer, and processor), each respondent was asked to rank various selection criteria, with one indicating the highest importance to ten indicating the criteria of lowest importance. Marketing and processing sectors ranked criteria based on purchasing decisions, while the production sectors ranked criteria based on selecting replacement breeding stock. Selection criteria for producers included live animal characteristics such as structural soundness and frame size. In contrast, things like purity and YLD were included in marketing and processing, but not production criteria. Selection criteria in all sectors included fiber diameter (FD), staple length (SL), SS, breed, U.S. indices, fleece weight (FW), and origin.

Participants were guided through two question sets to evaluate opinions on wool quality improvement across the U.S. wool flock and their personal flock such as: 1) “What is your opinion of the average FD represented in the U.S. wool flock?” and 2) “What is your opinion of the average FD represented in your flock?” Wool production respondents, commercial and seedstock, exclusively asked for trait opinions of their flock, except for yearling weight (YWT), which was asked of all production participants. Nevertheless, wool production, marketing, and processing respondents were asked for opinions of wool trait quality across the U.S. wool flock. Both sets addressed FD, SL, SS, FW traits, fleece character, and YLD. Both question types were scored using a 3-point Likert scale for either the respondent’s individual flock or the national flock ranging from 1: benefit from improved fleece trait, 2: satisfied with the fleece trait, and 3: not concerned with the fleece trait, where satisfaction meant respondents were satisfied with the current level or selection of the trait, and not concerned meant respondents were unconcerned with the level or direction of selection of the fleece trait. Two statement sets also considered the outcomes of stakeholder trait preferences, such as: 1) "I value FD over pounds of raw wool produced," and 2) "I believe wool producers, marketers, and processors would benefit from the development of a fine wool selection index that includes SL." Wool producers, marketers, and processors were asked to respond to these statements using a 7-point Likert scale which ranged from 1: being in strong agreement to 7: being in strong disagreement. The first statements determined the preference of FD, SS, fleece character, and YLD/CFW compared to grease fleece weight (GFW). The second set focused solely on FD, SL, and GFW.

The final set of statements determined stakeholder knowledge of the relationships between wool traits and body weight (BW) traits and respondents' preferences for the regulation of mature ewe size while simultaneously selecting for improved GFW and YLD. Wool production, marketing, and processing respondents were asked how much they agreed or disagreed with the statements, such as: 1) "Some of the traits that increase clean fleece weight include grease fleece weight, yearling weight, weaning weight, staple length, and frame size," 2) "Yield and grease fleece weight can be significant drivers in mature animal size and/or weight," and 3) "The fine wool index should account for the regulation of mature animal size and/or weight while simultaneously selecting for increases in yield and grease fleece weight." Respondents rated the level of agreement using a 7-point Likert scale, with 1: being in strong agreement to 7: being in strong disagreement.

Prior to survey distribution, a sub-group of 15 FWC members received the survey to ensure questions were well defined and that display logic and survey flow conditions were accurate and consistent. Modifications to the survey (i.e., flow, general edits, rearrangements, adjustments to display logic, as well as any additions) were all implemented based on suggestions from the sub-group. The final survey design applied extensive display logic and conditional branching, so respondents avoided irrelevant questions. Consequently, most statements required a response before moving on to the next set, while respondents with certain unanswered questions were directed to the last question set regarding the opinion and value of genetic selection.

Survey distribution

In January of 2020, at the annual American Sheep Industry (ASI) conference, the FWC met as a sub-committee to compile a list of stakeholders and industry representatives for survey distribution. The list included those in the U.S. fine wool sheep industry who may utilize or be impacted by the use of a fine wool selection index, such as producers, processors, and marketers. The purpose of the survey was explained to all those who received the survey link.

The survey was sent to 329 stakeholders via email, with a goal of receiving 200 responses. The survey remained open for 22 d, during which two reminders were sent to aid in survey completion rates on d 17 and d 21. After opening the survey, Qualtrics allowed respondents a 2-wk completion window before deemed incomplete. Of the 329 surveys distributed, 98 responses were received for a 30% response rate. Of those 98 responses, five surveys were deemed incomplete, while another two were under the age of 18, leaving 91 respondents for analysis.

Survey analysis

Survey results requiring categorical, yes/no, or subjective responses were assessed utilizing the statistical analysis software (SAS) Studio (SAS Institute Inc., Cary, NC) to evaluate frequency values as a number and percentage of the responses received for each categorical response. Microsoft Excel (Microsoft Corp., Redmond, WA) was also utilized to evaluate measures of central tendency, such as mean, median, and range, through descriptive analysis. The criteria ranking responses for each industry sector were combined into a weighted average ranking through Microsoft Excel and utilized to evaluate differences in selection criteria when making purchasing decisions. The rank was weighted for each answer choice (i.e., a preference between 1-13) according to the number of respondents that ranked each trait in each position. Production types were broken down into commercial, seedstock, and combined (producing for both seedstock and commercial use) to evaluate selection criteria decisions amongst producer types which included maternal, terminal, and wool production systems.

The question sets used to evaluate the opinions of wool trait quality improvement in personal producer flocks were analyzed using SAS Studio to evaluate the frequency of responses for all producers and the separated opinions of seedstock, commercial, and combination producers. Opinions of wool quality improvement in the U.S. flock were also analyzed using SAS Studio, but combined responses from marketers and processors, in addition to producers. Marketing and processing results were combined due to limited responses from either sector, with only five marketing and two processing participants. Responses to each set regarding wool trait quality opinions were recorded using a 7-point Likert scale, however, responses were condensed to a 3-point scale of agree, neither agree nor disagree, and disagree, due to the low number of responses in the marketing and processing sectors. The responses obtained within the strongly agree, agree, and somewhat agree categories from the 7-point scale were combined into an agree category, whereas the strongly disagree, disagree, and somewhat disagree categories were combined into a general disagree category within the 3-point scale. Those responses that replied with neither agree nor disagree remained within the same category, therefore no responses were removed from analysis during this process.

The statement sets evaluated trait preferences included in a fine wool index, trait preferences in comparison to GFW, and assessed stakeholder knowledge and preference for the regulation of mature ewe size were all analyzed using SAS Studio across all industry sectors to calculate frequency counts and percentages for each response. Like the wool quality improvement set, the production sector was evaluated as a whole and in relation to the branches of production, such as commercial and seedstock. As a result of low response rates, the marketing and processing sectors were combined, and all responses, regardless of sector, were consolidated from the 7-point Likert scale to a 3-point Likert scale in using the same method as the wool quality improvement set.

Results & Discussion

Demographics

In a larger survey of general sheep production completed in 2009 by ASI (ASI, 2010) 71.4% of respondents were older than 50, whereas the present survey resulted in a lower percentage (52 people; 59.8%) of participants over the age of 50. In the present survey, the mean age of respondents was 54 yr. The average years of involvement in the sheep industry among survey respondents was 32.5 yr, with a maximum of 75 yr and minimum of 3 yr (Figure 2.1). A majority of respondents in the present survey (45 people; 51.1%) had over 30 yr of experience in the sheep industry, similar to the 2009 survey results with 49.1% of respondents in the same category (ASI, 2010). According to these results and those reported in ASI (2010), the sheep industry is still represented by a majority of people over the age of 50 with more than 30 yr of experience.

The respondents were widely dispersed across the U.S. regardless of age, with responses being submitted from California to Massachusetts (Figure 2.2). Of the 90 surveys that included location information, over half (70%) indicated they were based in states west of the Mississippi River. The three states with the largest number of survey respondents were Texas (21.1%; 19

respondents), Montana (13.3%; 12 respondents), and South Dakota (12.2%; 11 respondents). The larger number of respondents from the Western U.S. was representative of the distribution of U.S. wool production, based on the fact 94.3% of respondents within the survey had a wool-producing source of income and the majority of wool production occurs in the western region of the U.S. according to the United States Department of Agriculture (USDA-NASS, 2021b). However, the distribution of respondents among western states, may not reflect the reality of wool production in western America, with few survey responses from the top four wool producing states (California, 2 responses; Colorado, 1 response; Wyoming, 3 responses; and Utah, 4 responses; USDA-NASS, 2021b). Reasons for the variation in survey responses from wool operations have been hypothesized as the following: larger size operations with fewer industry stakeholders in Wyoming, which may reduce the number of responses that were expected based on the large sheep population; a large percentage of the wool production estimates of Colorado and California are sourced from feedlots in the area, and potential lack of involvement or interest in genetic selection programs of NSIP from breed directories and associations among whose members the survey was distributed (USDA-NASS, 2021b,c).

Among the 82 respondents who reported sheep production as a primary source of income for their operation, 25 selected purebred/seedstock sheep production, 46 selected commercial sheep production, and 11 respondents selected both types of sheep production (reported in this study as combination producers). In comparison, only four respondents reported generating a portion of their income from processing, while seven respondents generated revenue through wool marketing. As a whole, 80.2% of all respondents reported that their main revenue stream was derived from a single source, whereas 15.4% claimed two or more sources, and 4.4% elected not to respond. Though seemingly disproportionate, the distribution of respondents between industry sectors was realistic, as most respondents were from the production sector, the largest stakeholder group in the U.S. (32,728 American wool producers; USDA-NASS, 2019). In comparison, there are approximately 100 wool marketing operations throughout the country, comprised of 25 buyers, 50 pools, and 30 warehouses (American Wool, 2016). Similarly, a 2016 survey of the U.S. mill inventory concluded there were approximately 92 wool processing mills in the country (Daniels et al., 2016). These sources (American Wool, 2016; Daniels et al., 2016) confirm the distribution of industry sectors responding to the survey. Primary income sources were used to further analyze survey data to compare preferences of wool traits and selection, including selection criteria ranking.

Selection criteria ranking

Producer responses

Of the 91 surveyed, only 76 were utilized in the evaluation of selection criteria ranking based on completion of the criteria ranking set by 69 production responses, 4 marketing responses, and 3 processing responses. All 69 production responses suggest that breed, structural soundness, weaning weight (WWT), and FD are the four most important selection criteria when selecting breeding stock (Table 2.1). The two most important selection criteria were breed and structural soundness regardless of production sector (commercial, seedstock, and combination). These results may indicate that when producers select replacement breeding stock, they prioritize the breed and adequate levels of structural correctness to survive and reproduce in their flock's environment. Though, due to the subjective nature of these traits, the degree of scrutiny placed on each trait will vary from producer to producer. For many producers, the endpoint of production is when the wool leaves the ranch and is acquired by the marketer (Lupton, 2015). This means that the ranking of selection criteria within this sector will be influenced by management factors and market prices. Management factors influence selection criteria as many producers are concerned with the development of replacement breeding stock as well as wool production. For this reason, they will be influenced by criteria other than wool traits, such as structural soundness and BW traits. In the case of BW, WWT may be a consideration for producers because it can be used to indicate mature ewe body size, which will impact costs through nutrition requirements and the management intensity required (Young et al., 2011). Differences occurred between production sectors regarding the third ranking criteria, however, as WWT was preferred by commercial (Table 2.2) and combination (Table 2.3) producers, and FD was preferred by seedstock producers (Table 2.4). Nevertheless, both WWT and FD ranked among the top five for all production sectors. The difference in the trait ranking of seedstock producers compared to commercial and combination producers is likely due to their production focus. The majority of seedstock producers (71.43%) who were included in the selection criteria ranking claimed to only have maternal or wool production type operations, whereas the commercial and combination production sectors had 47% and 50% of respondents, respectively, who indicated terminal production systems within their operation. These proportions may explain the differences between sectors, as the breeding objectives for each production system tend to be very different from one another. Brown et al. (2007) addressed the differences of each production system through the creation of terminal sire, maternal, and wool production indices within LAMBPLAN and MERINOSELECT. The breeding objectives for each were very different, with the terminal index focused on carcass merit and market weight, the maternal index focused on lamb production, and the wool production index focused on the improvement of wool production and quality traits (Brown et al., 2007). Due to seedstock producers focus on the sale of genetics to other producers, they may also place a higher preference on FD to maintain the average micron quality demanded by fine wool breed associations or for those who value fine wool quality (Burton et al., 2015). Additionally, breed character ranked among the top five most important criteria for selecting breeding stock across all production sectors and total responses. Among the lowest ranking criteria across all sectors and the total weighted average ranking were index values from the U.S. maternal, carcass plus, Western range index (WRI), and U.S. hair indices. When evaluating only the wool traits ranked, seedstock producers once again had slightly varied rankings compared to the other production sectors. Among the other production sectors, FD, GFW, SL, fiber uniformity, and SS ranked from higher to lower importance, respectively, while seedstock producers ranked fiber uniformity above GFW and SL. Market prices between wool and lamb likely have a significant impact on the ranking of selection criteria by producers. Though U.S. sheep producers are paid higher prices for lamb than wool, it has been shown that dual production for lamb and wool may be more resilient to market price changes (Warn et al., 2006). In addition, higher-quality wool will sell at premiums compared to lower quality wool, which is probably why producers consider wool quality traits, such as FD, when selecting replacement breeding stock. Overall, the ranking of traits within the production sector may be influenced by market prices for wool and lamb, and the limitations on selection such as unfavorable correlations between traits or a lack of accurate or cost-effective evaluation methods for traits.

Marketing responses

When asked to evaluate the importance of selection criteria in purchasing decisions, wool marketers ranked traits with significant economic impacts prior to and during processing highest (Table 2.5). This sector’s economic mindset was not surprising as marketers are considered the middleman for the sale of wool to domestic and international processing operations according to the National Research Council (NRC, 2008). The marketing sector generally deals with the preparation and transport of wool lots to the processor, which means that selection criteria when making purchases is largely dependent on preparation and transport costs and lot specifications (Lupton, 2015). The three most important criteria ranked by the marketing sector were FD, SL, and YLD, each of which contributes significantly to the economic value of wool. Fiber diameter may contribute over 75% of the total value of processed wool as it is directly correlated to processing performance and textile quality (Cottle, 2010). Staple length also impacts overall fleece value as an indicator of processing and product potential. Though not directly correlated to processing performance, YLD affects the shipping capacity and amount of usable wool that processors will receive as an indicator of CFW (Cottle, 2010). Fiber strength and character were also ranked in the top five selection criteria, likely because both are indicators of processing and end-product potential. Rottenbury et al. (1986) demonstrated the effects of SS on processing by testing different strength levels and positions of weakness in wool. The results confirmed that as SS was weakened, the average fiber length of top was reduced, and product loss increased. The effects of character on end-product potential were exhibited in McGregor and Postle (2007) when wool and cashmere of different crimp frequencies, or curvature (CURV), were processed and evaluated for roving and product quality. Results from this study indicated that CURV is a good indicator of hairiness and tenacity, with wool of lower CURV tending to have hairier, lower tenacity yarns and vice versa (McGregor and Postle, 2007). Though American producers get paid based on GFW, traits such as FD, SL, SS, character, and YLD influence the makeup of that price and are of greater economic importance to the marketing sector. Due to preparation and transport costs, YLD is a big consideration of wool marketers when making purchasing decisions, as it can impact the potential profit of a bale of wool. According to the Australian

Wool Exchange Limited (AWEX, 2009) wool is generally shipped either as raw greasy wool or semi processed wool that has at gone through a scouring process. In either situation the YLD is critical as, in a greasy wool shipment, it affects the amount of money that will be lost by shipping non-fiber components, and in semi processed wool, it affects the cost of preparation through scouring or carbonizing (Cottle, 2010). Despite this, results of this study indicated that FD and SL remain more important considerations for wool marketers, likely due to the specifications required by processors. The specifications of processors generally direct wool buyers on the weight, FD, SL, and minimum strength required of the sale lot, which supports the high rank of FD and SL in these results (Cottle, 2010). It is likely that SS is ranked below FD, SL, and YLD, because the specifications for SS are generally required at a minimum strength, meaning that any SS above that minimum would be acceptable. Overall, the top five selection criteria ranked by the marketing sector suggest that respondents are concerned with meeting order specifications of processors through traits that influence wool processing potential and the amount of usable product. The lowest ranking selection criteria by marketing respondents included breed, the WRI, and U.S. maternal index in order as the lowest ranking selection criteria.

Processor responses

The most important criteria to processing respondents suggests that wool traits impacting processing performance and end-product quality are of primary concern when making purchasing decisions. As the processing sector takes wool lots from the marketers and produces yarn for further textile use (Lupton, 2015), with selection criteria for purchases that is largely dependent on the final textile product desired. This is shown by the processing responses, as wool character and SL uniformity were ranked first and second, respectively, followed by FD and FD uniformity tied for third, and SL was fifth. Based on the goal of the processing sector, it was expected that character (color, crimp, and condition) was the highest-ranking trait for processors, with fleece uniformity and FD not far behind. The significant importance of character is due to the fact it can significantly affect the end product quality of wool textiles. For instance, when processors buy fine wool to create fine suits, preference will be given to superfine wool of lower CURV, whereas when processors are buying fine wool for knitwear products, processors may choose to purchase fine wool between 20 to 21 microns with a higher CURV (SGS, 2011; McGregor et al., 2015). Compared to the marketing sector, wool processors put more emphasis on the uniformity of SL and FD rather than YLD and SS. This is likely because issues from SS and YLD are removed by the marketing sector. For instance, when the SS of wool is low, marketers will create a pool of similarly weak SS, which is sold to processors who can utilize shorter fibers (Lupton, 2015). Yield is an important criterion for marketers because of the freight and scouring costs required to send the order to the processor (Simmons, 1980; Lupton, 2015). Instead of charging the processor directly for freight or preparation costs, the marketer will build the costs into a price for each lot of wool. Therefore, the processor is less concerned about the specific YLD of each bale but rather about the quality and overall cost. The processing sector places higher importance on fleece uniformity, likely because of its effect on final product quality (Wood, 2003). The focus on product quality also supports the low rankings of FW measurements, WRI, and the U.S. maternal index, as utilization is a concern prior to reaching the processor. Overall, while the rankings of all industry sectors may support the inclusion of FD in selection programs, these results also highlight the differences in trait priorities and variations among the production, marketing, and processing sectors surveyed.

Trait improvement opinions

Knowledge of stakeholder opinions on the status of wool quality traits in individual flocks and opinions of the overall U.S. wool flock are important considerations when new breeding objectives are developed. By evaluating industry representative's opinions, the importance of traits with an indirect economic impact or less recorded production data, such as CFW, YLD, and SS, can be considered in selection programs (Byrne et al., 2012a). Additionally, the incorporation of producer opinions in development can increase producer acceptance and utilization of breeding objectives (Nielsen & Amer, 2007).

Producer responses

Stakeholder opinions regarding wool trait improvement in the U.S. wool flock and individual producer flocks were analyzed to assess which wool traits should be emphasized in selection. Wool producers were the only group to be asked about their individual flocks. Opinions of FD, SS, and character in individual flocks were similar amongst the production sector as most wool production respondents (61.5%, 74%, and 65.4%, respectively) reported to be satisfied with the current quality of those traits. However, 77.55% and 53.06% of all wool production respondents voted that FD and character, respectively, would benefit from improvement in the U.S. wool flock. A majority of commercial (55.17%) and combination (71.43%) producers suggested that SS could benefit from improvement in the U.S. flock, while most seedstock producers (61.54%) felt that the SS of the U.S. flock was suitable.

Unlike FD, SS, and character, questions regarding FW and YLD of individual flocks reported few differences amongst production sectors. Regardless of production sector, most respondents indicated that they would benefit from improved YLD and FW, but for seedstock producers, 50% reported satisfaction with current FW, with the other half indicating that their own flock would benefit from increased FW. Similarly, commercial producers reported that half were satisfied by the current YLD of their flock, while the other half felt they would benefit from increased YLD. When considering improvements to the U.S. wool flock, 79.59% and 68% of all wool production respondents indicated a benefit from improved YLD and FW, respectively, with similar outcomes across production sectors.

Of all wool production respondents, the majority (56%) indicated that they were satisfied with the SL of their flocks compared to 40% indicating a benefit from the improvement of SL in their flock (4% noted they were not concerned about SL in their flock; Figure 2.3). When responses were evaluated based on production sector, however, differences concerning SL quality occurred. The majority (62.07%) of commercial producers indicated that they were satisfied with the current SL in their flocks; however, 50% of seedstock producers were satisfied with the current SL, and 50% felt improvement of SL in their own flock was needed (Figure 2.3). Respondents in the combination production sector indicated that they would benefit from improved SL by a slight majority (57.14%). Despite differences in opinion of SL amongst individual flocks, the majority (77.55%) of producers across all production sectors felt the U.S. flock could benefit from improved SL (Figure 2.3).

Even with differences in the responses regarding individual flocks, results indicate that FD, SS, character, YLD, SL, and FW should be improved within the U.S. wool flock. Responses on an individual flock basis were not included in the decision to incorporate traits in a genetic selection index, because the index will be applied to selection of the entire NSIP fine wool population rather than individual flocks. Nevertheless, responses by wool producers regarding their own flocks gave insight into the potential usage of a proposed fine wool index. Responses for wool trait improvement by wool producers regarding their own flock suggest that the inclusion of FW traits and YLD would be the most favorable choices for inclusion in the index.

In addition to fleece traits, all production respondents were asked for opinions of the current YWT of their individual flocks. Regardless of production sector, most respondents (67.61%) indicated that they were satisfied with the YWT of their flock (Figure 2.4). Of the remaining respondents, 9.86% reported that higher YWT would be preferable, 9.86% favored the selection of lighter YWT, and 12.68% of respondents were not concerned about the YWT of their flock.

Processing & Marketing responses

Trait improvement questions were also asked of processors and marketers to better understand the industry sectors' opinions regarding trait quality of the entire U.S. wool flock. Analysis combined marketing and processing results due to a low number of responses for either sector, with only five marketing and two processing responses. Nevertheless, the majority of marketing and processing respondents reported that the U.S. wool flock would benefit from improved FD (71.43%), SS (71.43%), fleece character (85.71%), YLD (100%), SL (71.43%), and FW (71.43%) characteristics. Similar to production responses for the U.S. flock, these results further support the inclusion of FD, SS, fleece character, YLD, SL, and FW in future genetic selection programs as a way to improve the U.S. wool flock.

Overall, results indicated that a majority of all stakeholders feel the need to improve FD, SS, character, YLD, SL, and FW of the U.S. wool flock. While improved FD, SL, and GFW can occur through NSIP EBV measurements (Notter and Lewis, 2018), CFW, SS, overall character, and YLD have yet to be incorporated into NSIP due to lack of data collected and cost of measurements. One of the largest limitations faced is the lack of collected phenotypic data or available NSIP EBV for YLD or CFW. While CFW and YLD can be assessed through the measurement of a wool base (the weight of wool fibers without any non-fiber components) and vegetable matter (VM) base (the weight of all organic materials within a wool sample) in a wool lab (Lupton, 1987), the calculation requires precise measurement and can be expensive when considering the improvement of a population. Until they are incorporated into NSIP, producers can improve CFW and YLD through proper management practices, such as skirting and crutching, and possibly using indirect selection of increased SL (Lupton, 2015).

Unlike CFW and YLD, there was no method currently available in the U.S. to objectively assess the SS or overall character of wool due to its composition of multiple traits. While SS is a critical aspect of wool value, it does not decrease the value of wool until it becomes extremely tender or has a break (Lupton, 1987). The SS can typically be assessed visually by stretching a staple, but it is not as accurate as objective SS measurement defined in N per kilotex (ktex). Still, improvement of SS can be made by providing flocks with proper nutrition and low stress environments during the wool growth cycle (Cottle, 2010). Though there is no objective measurement for overall character, traits under character, such as crimp and uniformity may be assessed using either fiber diameter coefficient of variation (FDCV) or CURV, while color may be assessed visually (Cottle, 2010). Though CFW, YLD, SS, and overall character are unable to be included in genetic selection programs without further research, improvement can be made in each trait through proper management, evaluation of associated traits, or though visual selection.

Trait preferences

Respondents were asked a series of questions regarding their preferences for certain wool traits to reinforce industry representatives' trait quality opinions and compare industry sector preferences for certain wool traits. This set of statements included queries about stakeholder's preferences of traits they believe should be included in a fine wool index and their preference of wool traits over GFW. Additional questions examined stakeholder knowledge of the relationships between BW traits and wool traits along with preferences for constraints of mature ewe size. Analysis combined marketing and processing results due to a low number of responses for either sector, with only five marketing and two processing responses.

High priority trait inclusion

A majority of all wool production respondents agreed that producers, marketers, and processors would benefit from the inclusion of GFW (79.6%), FD (89.8%), and SL (88%) in a fine wool selection index, regardless of production sector (Figure 2.5). The combined marketing and processing responses also agreed with the production sector, as 71.4% of respondents agreed to the benefit of each trait's inclusion in the fine wool index (Figure 2.5). The results of all industry sectors regarding GFW inclusion in a fine wool index supported previous opinions indicating GFW improvement would benefit the U.S. wool flock and individual wool producers' flocks. Producer responses for the inclusion of FD and SL in a fine wool index, however, were contrary to producer opinions that indicated they were satisfied with the current FD and SL of their own flocks. The conclusion could be drawn that, though producers felt that FD and SL quality were satisfactory in their flocks, they may not oppose the potential improvement or maintenance of FD and SL through a fine wool selection index.

Stakeholder approval of the inclusion of GFW, FD, and SL is critical to the success of a fine wool index based on the large percentage of economic value that each of these traits have on fine wool production. In fact, FD is the primary economic determinant of wool quality that makes up two-thirds of the value of wool top (Iman et al., 1992). Fiber diameter is the basis in which global market prices are set, as it indicates processing efficiency, spinning quality, end-product textile quality, and is used to determine what processing capacity wool is best suited towards. Based on the importance of FD within the industry, it needs to be included in the fine wool index. Given the lack of an American based CFW EBV, GFW should also be included in the breeding objective. Heavier GFW is advantageous to the producer because they are paid on a per-pound basis (Wilson and Morrical, 1991). However, when selecting for heavier GFW it is important to maintain an adequate YLD, as fleeces with extremely low YLD will receive heavy discounts. In addition to GFW and FD, SL is also a significant contributor to economic value, and is also used as an indicator of processing and product potential (Lupton, 1987). Based on the important contributions of FD, GFW, and SL to economic value, production and quality, all traits should be included in the index. The responses of participants support these inclusions and indicate that producers will accept and utilize an index that includes FD, GFW, and SL.

Preferences of wool traits in comparison to grease fleece weight

A majority of producer responses valued FD (64%), character (68%), and YLD (82%) over GFW, irrespective of production sector (Figure 2.6). These were similar for the combined responses of marketers and processors, with a majority that valued FD (71.43%), character (57.17%), and YLD (100%) over GFW (Figure 2.6). Though expected for marketers and processors, production responses for the valuation of FD, character, and YLD over GFW indicated that producers place higher emphasis on wool quality rather than the GFW. This support of wool quality traits is likely because, while producers are paid on a GFW basis, wool with higher quality will sell for higher prices over that of lower quality. Burton et al. (2015) supported this argument in terms of FD in a retrospective study evaluating over 50 yr worth of Wyoming ram test data. Analysis of the ram test data showed that, though the lamb market had been higher than the wool market, FD remained stable over the years. Authors speculated that even in a market driven towards lamb production, producers would continue to maintain fine wool as it still earned a higher price over coarser wool (Burton et al., 2015).

Though most respondents agreed they valued SS over GFW, there was more variation in responses amongst production sectors. Combination and commercial producers valued SS over GFW, with 85.7% and 51.7% of respondents, respectively (Figure 2.7). Seedstock producers were divided in their responses, as 35.7% said they valued SS over GFW, and 35.7% responded that they had no preference, some even reported that they valued GFW over SS (28.6%). The divergence seen in these results is likely due to the seedstock sectors focus on selling genetics, while commercial and combination producers focus on selling wool products. As seedstock producers focus on genetics, they may tend to be more concerned with lifetime wool production and genetic effects that reduce production. With a heritability of 0.13 (Wuliji et al., 2001), SS is primarily controlled by the environment rather than additive genetic effects, which supports the idea that seedstock producers may be more concerned about GFW than SS. Lower SS wool is produced by a disruption during the wool growth cycle, which can be caused by lack of nutrition, illness, pregnancy, and other environmental sources (Lupton, 2015). Commercial and combination producers are likely more concerned with SS, because the presence of a break due to nutrition or stress may occur throughout the entire flock, reducing the profit made from the annual wool clip.

Despite the divided responses of seedstock producers, these results suggest a majority of the combined marketing and processing sector as well as the production sector value wool FD, character, YLD, and SS over GFW, indicating that most wool stakeholders' value CFW and wool quality traits over total pounds of raw wool. Overall, responses from this section further support the inclusion of FD, character, YLD, and SS in future genetic selection programs.

Mature ewe size and relationship between frame size and wool traits

Just as the evaluation of wool quality and production preferences are important, so is the evaluation of stakeholder understanding of how BW impacts wool quality and preferences regarding the regulation of mature ewe size. Selection for increased BW is known to have positive correlations with FW and SL but will have an antagonistic relationship with FD (Lupton, 2015), and therefore, needs to be regulated if response to wool trait selection is going to be maximized. A majority of all respondents (73.68%) agreed the traits increasing CFW include GFW, YWT, WWT, SL, and frame size, regardless of their industry or production sector.

When asked whether YLD and GFW were significant drivers of mature ewe size, responses varied among industry and production sectors. While 57.1% of combination producers agree that YLD and GFW are significant drivers of mature ewe size, seedstock and commercial producers were divided in their responses with only 35.71% and 44. 83% who agreed, respectively (Figure 2.8). Overall, only 44% of all production respondents agreed that YLD and GFW were significant drivers of mature ewe size. In contrast, combined marketing and processing sectors reported 42.9% of respondents in agreement, 28.6% of respondents specified that they neither agreed nor disagreed with the statement, and 28.6% disagreed with the statement (Figure 2.8). The majority of marketing and processing responses suggest that misunderstandings of the relationship between BW and wool traits extends beyond the production sector. However, as the marketing and processing sectors do not have information or make decisions regarding live animal development (Lupton, 2008), these results could indicate a disconnect between some wool marketers and processors with the live animal production aspect of the industry.

Due to the correlations between BW and wool traits, index developers have considered potential BW regulation in the fine wool selection index. Before inclusion can occur, however, future research is needed to gain the accurate economic information required. The future success of an index that includes BW regulations may also depend, in part, on stakeholders' awareness of the relationships between wool and other production traits. Nevertheless, the preferences of industry stakeholders need to be considered, as breeding objectives are less likely to be achieved if developers ignore the preferences of industry representatives and trait inclusions are strongly opposed (Byrne et al., 2012b).

To evaluate participants preferences of BW regulation in the fine wool index, respondents were asked if the fine wool index should account for the regulation of mature animal size and/or weight, while also increasing YLD and GFW. When production sectors were evaluated, a majority of the commercial (65.5%) and combination (57.1%) wool production respondents agreed that mature animal size should be regulated in a fine wool index while simultaneously selecting for increased YLD and GFW (Figure 2.9). In contrast, only 35.71% of seedstock producers indicated that they agreed with the statement (42.86% neither agreed nor disagreed). Responses by seedstock wool producers may have been inconsistent, but only 10% of all wool production respondents reported that they disagreed with the regulation of mature animal size while selecting for increased YLD and GFW. Based on these results, it seems that most wool producers would favor regulating mature BW within a fine wool index while increasing GFW and YLD. It was also hypothesized that the combined marketing and processing sectors would agree to the regulation of mature animal size while simultaneously selecting for increased YLD and GFW, and thus CFW. However, responses were divided with 42.86% of respondents agreeing with the statement, 42.86% of respondents disagreeing, and

14.29% who had no preference (Figure 2.9). These responses were unexpected, but as processors and marketers will not take part in live animal development, it will be more important to focus on responses from the wool production sector.

According to the results of this survey section, a majority of respondents in the combined processing and marketing sector and production sector understand how BW traits affect CFW; however, fewer respondents seemed to be aware of how the improvement of fleece traits can drive changes in BW traits. Based on the divided responses of the production and combined marketing and processing sectors, there is a need for more outreach or extension programs to explain the relationship between BW traits and wool traits and why those relationships occur. Awareness of the relationships between mature BW and fleece traits are essential to managing the indirect selection response in traits, as the response to selection may be reduced or yield undesirable changes in traits if not considered (MacNeil et al., 1997). With index selection, only a few traits are included in the breeding objective, and the relationships of those traits are accounted for by including the genetic and phenotypic (co)variances. However, many traits not accounted for may have an associated change based on selection of an index. For instance, when selection occurs on an index that includes GFW, SL, and FD, there will likely be an increase in BW as a result, which, if left unchecked for a few generations, can lead to much larger BW. Selection for much larger BW risks problems with structural soundness and cost increases due to the increased nutritional requirements for that animal. Negative impacts on other traits due to selection without considering the associated outcomes have been documented in dairy cattle when fertility was reduced due to increased milk production (Walsh et al., 2011). Concerns of unwanted selection outcomes due to correlations with traits outside of the index could be addressed during promotion of the index at various meetings. Overall, these results demonstrate the need for further outreach addressing the relationships of wool traits with other production traits, such as BW, and may generate greater acceptance of a selection index including restricted BW.

Conclusion

The national wool production survey of industry stakeholders was used to evaluate wool stakeholder's trait preferences, compare the preferences of representatives in the marketing, processing, and production sectors of the wool industry, and assist in the definition of a fine wool breeding objective. Evaluation of stakeholder responses indicated that the majority of respondents would favor an index that selects for improved FD, GFW, SL, SS, character, and YLD while restricting mature BW. However, this list needs additional consideration due to the constraints of the NSIP database before further development of an index is considered.

The limitations of the NSIP database and trait groupings affected trait utilization of the fine wool selection index under development. The largest limitation is the lack of collected phenotypic data or an available NSIP EBV for YLD, CFW, or overall character. Future research concerning more cost-effective testing methods for CFW and creation of a CFW EBV is needed before incorporation of CFW and YLD characteristics in index selection can occur. Though there is no evaluation for overall character, the EBV of CURV and FDCV can be used evaluate partial character.

Aside from wool traits, producers may want to regulate changes in mature BW due to selection on wool quality traits. Due to the lack of available market information and complex effects of wool production, reproduction, nutrition, and environment on mature BW, inclusion into an index will be difficult. Further research is needed to accurately estimate the economic impact of BW on fine wool production before it can be meaningfully incorporated into a fine wool index.

After considering the modifications and stakeholder preferences, traits identified for further development of a fine wool selection index a FD, GFW, SL, FDCV, CURV. As the survey is not a purely economic method of deriving suggested traits for a breeding objective, further research is needed to validate traits economically and derive REV. Nevertheless, future genetic selection and outreach programs based on these results should align more closely with the preferences and needs of wool industry stakeholders across production, marketing, and processing, rather than just in production sectors.

References

American Sheep Industry (ASI). 2010. American Sheep Industry Survey: Individual Sheep Production Information, Sheep Industry Expansion, Farm/Ranch Purchases, Livestock Protection. American Sheep Industry, Englewood, CO. Available from: http://d1cqrq366w3ike.cloudfront.net/http/DOCUMENT/SheepUSA/ASI_Survey_Results.pdf (Accessed 16 July 2021.)

ASI. 2014. Code of practice for preparation of wool clips. American Sheep Industry, Englewood, CO. Available from: http://d1cqrq366w3ike.cloudfront.net/http/DOCUMENT/SheepUSA/Code_of_Practice_low.pdf (Accessed 19 June 2021.)

American Wool. 2016. American wool production. American Sheep Industry: American Wool Council, Englewood, CO. Available from: https://d1cqrq366w3ike.cloudfront.net/http/DOCUMENT/SheepUSA/international%20wool%20brochure%202016%20low%20res.pdf (Accessed 05 August 2021.)

Australian Wool Exchange Limited (AWEX). 2009. The Australian wool market: An introduction for prospective participants. Available from: http://www.awex.com.au/media/1041/wool-buying-in-australia-2013.pdf (Accessed 13 April 2022.)

Bourdon, R. M. 1998. Shortcomings of current genetic evaluation systems. J. Anim. Sci. 76:2308-2323. doi: https://doi.org/10.2527/1998.7692308x

Brown, D. J., A. E. Huisman, A. A. Swan, H. U. Graser, R. R. Woolaston, A. J. Ball, K. D. Atkins, and R. G. Banks. 2007. Genetic evaluation for the Australian sheep industry. Proc. Assoc. Advmt. Anim. Breed. Genet. 17:187-194. Available from: https://www.academia.edu/download/43450546/Genetic_evaluation_for_the_Australian_sh20160307-9576-wlntey.pdf (Accessed 13 June 2021.)

Burton, D. J., P. A. Ludden, R. H. Stobart, and B. M. Alexander. 2015. 50 years of the Wyoming ram test: How have sheep changed. J. Anim. Sci. 93:1327–1331. doi: https://doi.org/10.2527/jas.2014-8150

Byrne, T. J., P. R. Amer, K. F. Smith, P. F. Fennessy, and P. Hansen. 2012a. Using preference survey approaches to define breeding goals. In: Proc. 38th ICAR. Cork, Ireland. Available from: https://www.icar.org/wp-content/uploads/2015/09/Byrne1.pdf (Accessed 15 March 2021.)

Byrne, T. J., P. R. Amer, P. F. Fennessy, P. Hansen, and B. W. Wickham. 2012b. A preference-based approach to deriving breeding objectives: applied to sheep breeding. Animal 6(5):778-788. doi: 10.1017/S1751731111002060

Cottle, D. J. 2010. Wool preparation, testing and marketing. In: D. J. Cottle, Ed., Int. Sheep and Wool Handbook. Nottingham University Press, Nottingham, UK. p. 581- 618.

Daniels, J., T. Meinert, M. Bartsch, R. Burgess, C. Erichsen, and D. Kahn. 2016. National mill inventory: An exploratory representation of United States fiber processing. Fibershed. San Geronimo, California. Available at: http://fibershed.org/wp-content/uploads/2016/12/Mill-Inventory-Report.pdf (Accessed 05 August 2021.)

Duguma, G., T. Mirkena, A. Haile, A. M. Okeyo, M. Tibbo, B. Rischkowsky, J. Solkner, and M. Wurzinger. 2011. Identification of smallholder farmers and pastoralists' preferences for sheep breeding traits: choice model approach. Animal 5(12):1984-1992. doi: 10.1017/S1751731111001029

Fuerst-Waltl, B., C. Fuerst, W. Obritzhauser, and C. Egger-Danner. 2016. Sustainable breeding objectives and possible selection response: Finding the balance between economics and breeders' preferences. J. Dairy Sci. 99:9796-9809. doi: https://doi.org/10.3168/jds.2016-11095

Gizaw, S., H. Komen, and J. A. M. van Arendock. 2009. Optimal village breeding schemes under smallholder sheep farming systems. Livest. Sci. 124:82-88. doi: https://doi.org/10.1016/j.livsci.2009.01.001

Hazel, L. N. 1943. The genetic basis for constructing selection indexes. Genetics. 28:476-490.

Iman, N. Y., C. L. Johnson, W. C. Russell, and R. H. Stobart. 1992. Estimation of genetic parameters for wool fiber diameter measures. J. Anim. Sci. 70:(4)1110-1115. doi: https://doi.org/10.2527/1992.7041110x

Just A., R. Wellmann, and J. Bennewitz. 2018. Estimation of relative economic weights and the marginal willingness to pay for breeding traits of Brown Swiss cattle using discrete choice experiments. J. Dairy Sci. 101:5207-5213. doi: https://doi.org/10.3168/jds.2017-14012

Lupton, C. J. 1987. The role of objective measurements in wool research and marketing. SID Res. Dig. 3(3):21-25.

Lupton, C. J. 2008. ASAS CENTENIAL PAPER: Impacts of animal science research on United States sheep production and predictions for the future. J. Anim. Sci. 86:3252-3274. doi: 10.2527/jas.2008-1148

Lupton, C. J. 2015. Wool chapter. In: SID sheep production handbook, vol. 8, 2015 Edition. American Sheep Industry Association, Fort Collins, CO. p. 1001-1064.

MacNeil M. D., R. A. Nugent, and W. M. Snelling. 1997. Breeding for profit: an introduction to selection index concepts. Range Beef Cow Symposium. 142. Available from:

https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1141&context=rangebeefcowsymp (Accessed 15 November 2019)

McGregor, B. A. and R. Postle. 2007. Wear attributes of cashmere single jersey knitted fabrics blended with high and low crimp superfine merino wool. Text. Res. J. 79(10):876-887. doi: 10.1177/0040517509103948

McGregor, B. A., A. Doughty, J. Thompson, M. Naebe, and D. Tester. 2015. Effects of variation in wool fiber curvature and yarn hairiness on sensorial assessment of knitted fabrics. Text. Res. J. 85(11):1153-1166. doi: 10.1177/0040517514566112

National Research Council (NRC). 2008. Changes in the sheep industry in the United States: Making the transition from tradition. National Academies Press. Washington, D.C. p. 247-258. doi: https://doi.org/10.17226/12245

NSIP. 2019. Fine Wool Consortium. American Sheep Convention. New Orleans, Louisiana. Available from: https://d1cqrq366w3ike.cloudfront.net/http/DOCUMENT/SheepUSA/Fine%20Wool%20Consortium%20Grant2%201-25-19%20(1).pdf (Accessed 25 November 2019.)

Nielsen H. M. and P. R. Amer. 2007. An approach to derive economic weights in breeding objectives using partial profile choice experiments. Animal. 9:1254-1262. doi: https://doi.org/10.1017/S1751731107000729

Notter, D. R. and R. M. Lewis. 2018. NSIP EBV notebook. Retrieved from: http://nsip.org/wp-content/uploads/2019/01/NSIP-EBV-Descriptions-Update-16-Dec-2018.pdf. (Accessed 22 January 2020.)

Ochsner, K. P., M. D. MacNeil, R. M. Lewis, and M. L. Spangler. 2017. Economic selection index development for Beefmaster cattle II: General-purpose breeding objective. J. Anim. Sci. 95:1913-1920. doi: 10.2527/jas2016.1232

Pearson, R. E. 1982. Economic aspects of the choice of a breeding objective. Proc. 2nd World Congr. Genet. Appl. Livest. Prod. Madrid, Spain. 6:50-59. Available from: http://www.wcgalp.org/system/files/proceedings/1982/economic-aspects-choice-breeding-objective.pdf (Accessed 15 October 2019.)

Rottenbury, R. A., W. J. Kavanagh, J. R. Eley, and M. W. Andrews. 1986. The effect of the strength properties of wool staples on the worsted processing part II: The location of staple weakness. J. Text. Inst. 77(3): 191-200. doi: 10.1080/00405008608658409

Santos, B., J. A. Archer, D. Martin-Collado, C. D. Quinton, J. Crowley, P. R. Amer, and S. Miller. 2019. Industry consultation survey for the American Angus $value indexes review. Proc. Assoc. Advmt. Anim. Breed. Genet. 23:55-58. Available from:

https://www.cabdirect.org/cabdirect/FullTextPDF/2020/20203356241.pdf (Accessed 15 March 2021.)

SGS. 2011. Curvature. Wellington, New Zealand. SGS Wool Testing Services. Available from: https://www.sgs.co.nz/-/media/local/new-zealand/documents/technical-documents/technical-bulletins/wool-testing-info-bulletins/sgs-agri-fibre-curvature-a4-en-11-v2.pdf (Accessed 19 May 2021.)

Simmons, P. 1980. Determination of grade prices for wool. Rev. Mark. Agric. Econ. 48:37-46. Available from: https://ageconsearch.umn.edu/record/9345/files/48010037.pdf (Accessed 29 January 2022.)

Swan, A. A., I. W. Purvis, and L. R. Piper. 2008. Genetic parameters for yearling wool production, wool quality and body weight traits in fine wool Merino sheep. Aust. J. Exp. Agric. 48:1168-1176. doi: https://doi.org/10.1071/EA07425

USDA-ERS. 2020. U.S. supply and use estimates and prices. Available from: https://www.ers.usda.gov/webdocs/DataFiles/48516/U.S.WoolSupplyandDemand.xlsx?v=5600.8 (Accessed 14 March 2021.)

USDA-NASS. 2019. 2017 Census of agriculture: United States summary and state data. Washington D.C. AC-17-A-51. Available from: https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (Accessed 01 August 2021.)

USDA-NASS. 2021b. Sheep and goats. Fort Collins, CO. N1949.1611 Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/000000018/41688945h/f47539332/shep0121.pdf (Accessed 10 February 2021.)

USDA-NASS. 2021c. Livestock slaughter: 2020 summary. Fort Collins, CO. 0499-0544. Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/r207tp32d/sj139x554/7w62g4561/lsan0421.pdf (Accessed 03 August 2021.)

Walsh, S. W., E. J. Williams, and A. C. O. Evans. 2011. A review of the causes of poor fertility in high milk producing dairy cows. Anim. Repro. Sci. 123:127-138. doi: 10.1016/j.anireprosci.2010.12.001

Warn, L. K., K. G. Geenty, and S. McEachern. 2006. What is the optimum wool–meat enterprise mix? Int. J. Sheep Wool Sci. 54:40-49. Available from: https://sheepjournal.net/index.php/ijsws/article/view/705/705 (Accessed 15 January 2022.)

Wilson, D. E. and D. G. Morrical. 1991. The national sheep improvement program: a review. J. Anim. Sci. 69:3 872-3881. doi: https://doi.org/10.2527/1991.6993872x

Wood, E. 2003. Textile properties of wool and other fibres. Wool Tech. and Sheep Breed. 51(3):272-290. Available from: https://www.sheepjournal.net/index.php/WTSB/article/view/1711/1699 (Accessed 03 March 2021.)

Wuliji, T., K. G. Dodds, J. T. J. Land, R. N. Andrews, and P. R. Turner. 2001. Selection for ultrafine Merino sheep in New Zealand: heritability, phenotypic and genetic correlations of live weight, fleece weight and wool characteristics in yearlings. Anim. Sci. 72:241-250. doi: https://doi.org/10.1017/S1357729800055739

Young, J. M., A. N. Thompson, M. Curnow, and C. M. Oldham. 2011. Whole-farm profit and the optimum maternal liveweight profile of Merino ewe flocks lambing in winter and spring are influenced by the effects of ewe nutrition on the progeny's survival and lifetime wool production. Anim. Prod. Sci. 51:821-833. doi: 10.1071/AN10078

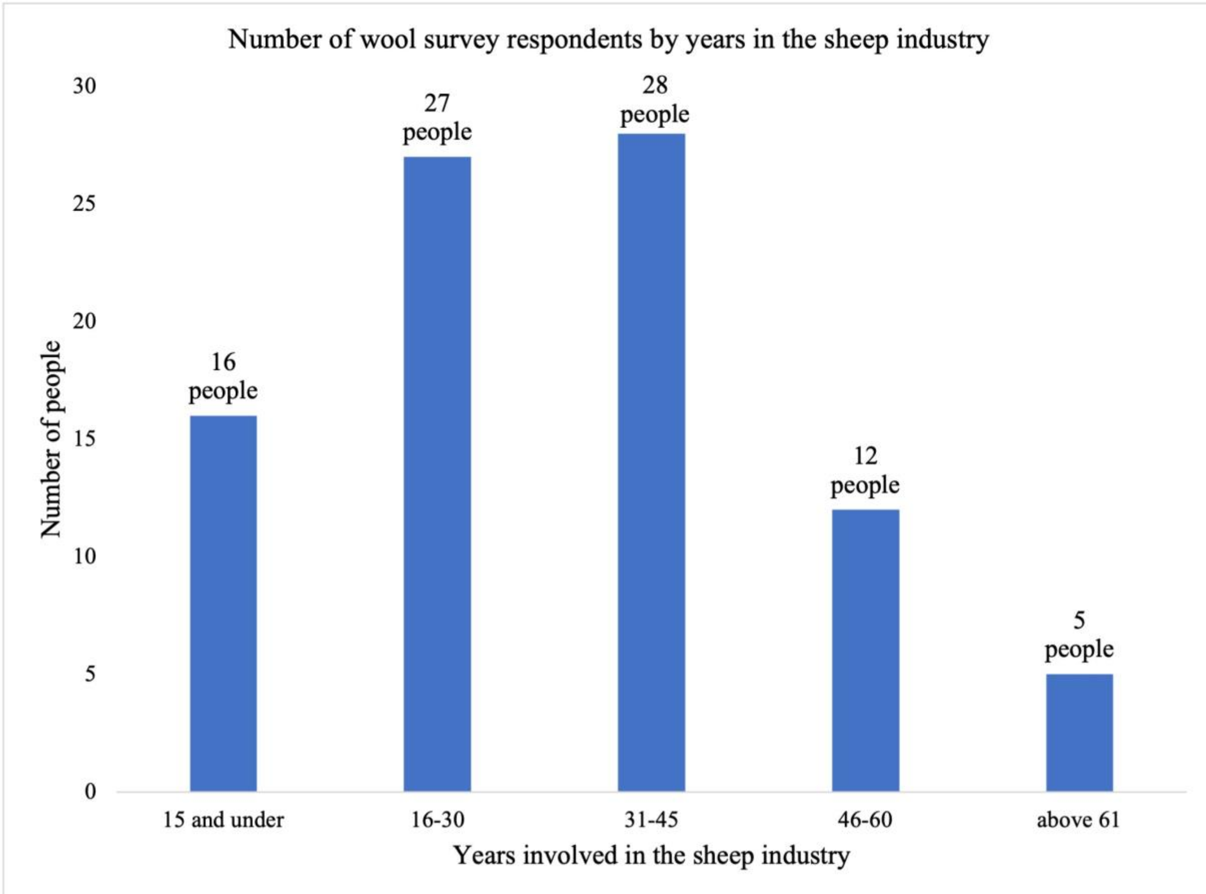

Figure 2.1 Number of national wool production survey respondents by years in the sheep industry

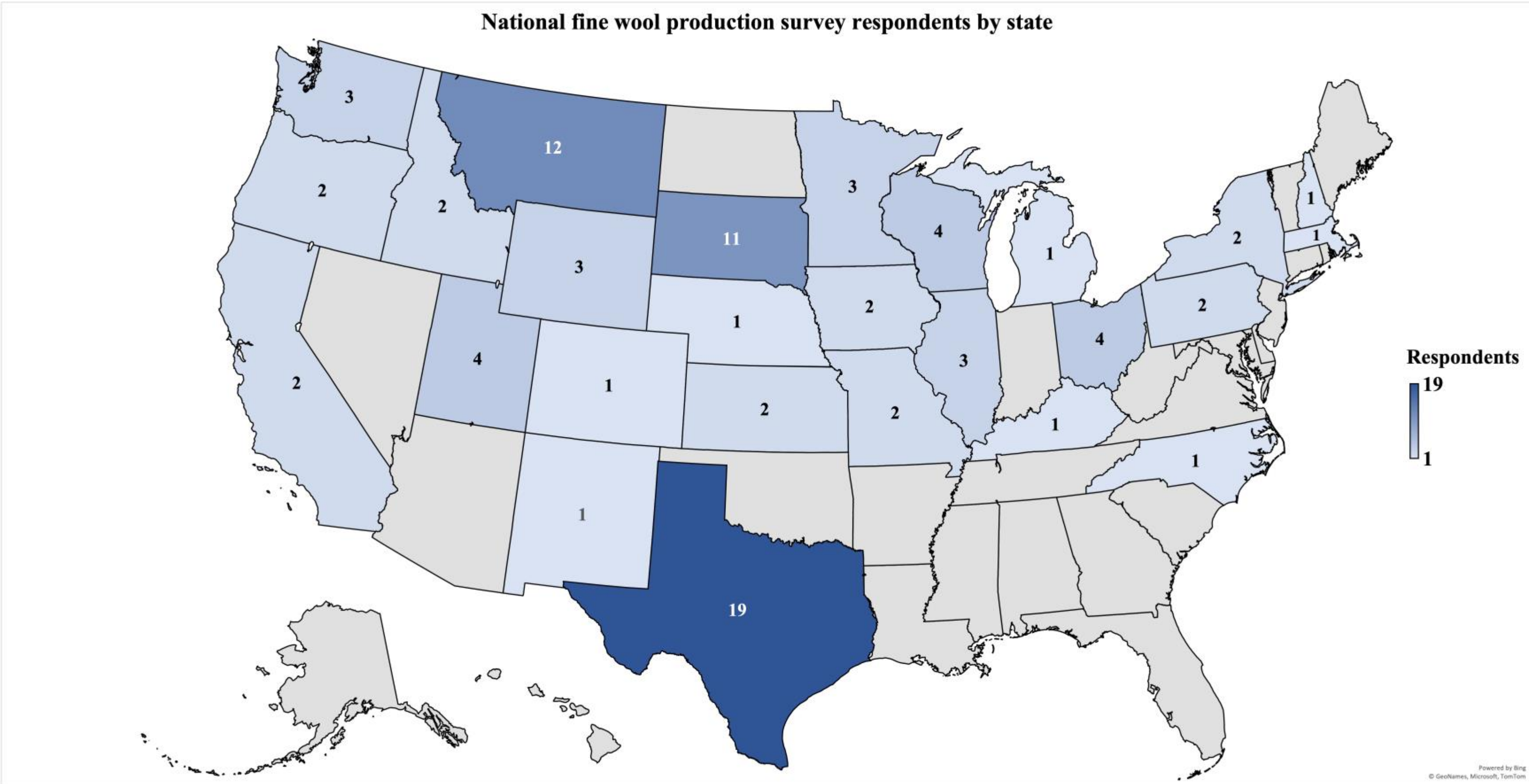

Figure 2.2 Map of National wool production survey respondents by state

Table 2.1 All producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock

All Producers	
Selection Criteria	**Rank**
Breed	1
Structural Soundness	2
Weaning Weight	3
Fiber Diameter	4
Breed Character	5
Grease Fleece Weight	6
Staple Length	7
Fleece Uniformity	8
Origin	9
Frame Size	10
Yearling Weight	11
Staple Strength	12
Carcass Plus Index	13
U.S. Western Range Index	14
U.S. Maternal Index	15
U.S. Hair Index	16

Table 2.2 Commercial producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock

Commercial Producers	
Selection Criteria	**Rank**
Breed	1
Structural Soundness	2
Weaning Weight	3
Fiber Diameter	4
Breed Character	5
Grease Fleece Weight	6
Staple Length	7
Fleece Uniformity	8
Frame size	9
Origin	10
Yearling Weight	11
Staple Strength	12
USA Maternal Index	13
Carcass Plus Index	14
USA Western Range Index	15
USA Hair Index	16

Table 2.3 Combination producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock

Combination Producers	
Selection Criteria	**Rank**
Breed	1
Structural Soundness	2
Weaning Weight	3
Breed Character	4
Fiber Diameter	5
Grease Fleece Weight	6
Yearling Weight	7
Origin	8
Frame size	9
Staple Length	10
Fleece Uniformity	11
Staple Strength	12
Carcass Plus Index	13
USA Maternal Index	14
USA Western Range Index	15
USA Hair Index	16

Table 2.4 Seedstock producer respondents (weighted average) rankings of various criteria for selecting replacement breeding stock

Seedstock Producers	
Selection Criteria	**Rank**
Breed	1
Structural Soundness	2
Fiber Diameter	3
Weaning Weight	4
Breed Character	5
Fleece Uniformity	6
Grease Fleece Weight	7
Staple Length	8
Origin	9
Yearling Weight	10
Frame size	11
Staple Strength	12
USA Western Range Index	13
Carcass Plus Index	14
USA Maternal Index	15
USA Hair Index	16

Table 2.5 Marketing respondents (weighted average) rankings of various criteria for making purchasing decisions

Wool Marketing	
Selection Criteria	**Rank**
Fiber Diameter	1
Staple Length	2
Yield	3
Staple Strength	4
Character	5
Uniformity of Fiber Diameter	6
Uniformity of Staple Length	7
Origin (producer)	8
Purity	9
Fleece Weight	10
Breed	11
USA Western Range Index	12
USA Maternal Index	13

Table 2.6 Processing respondents (weighted average) rankings of various criteria for making purchasing decisions

Wool Processing	
Selection Criteria	**Rank**
Character	1
Uniformity of Staple Length	2
Fiber Diameter	3
Uniformity of Fiber Diameter	4
Staple Length	5
Staple Strength	6
Origin (producer)	7
Yield	8
Purity	9
Breed	10
Fleece Weight	11
USA Western Range Index	12
USA Maternal Index	13

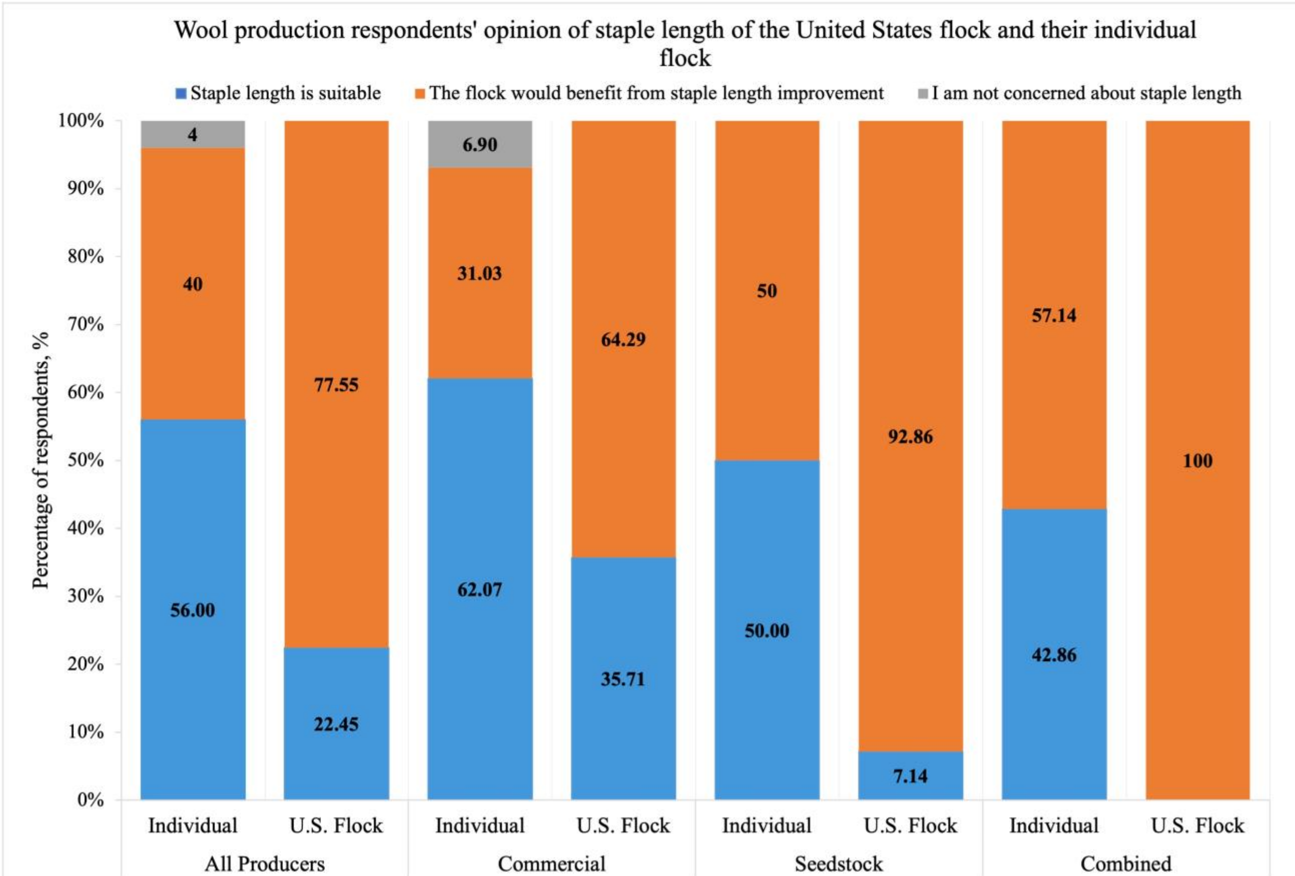

Figure 2.3 Wool production respondents' opinion of staple length of the United States flock and their individual flock

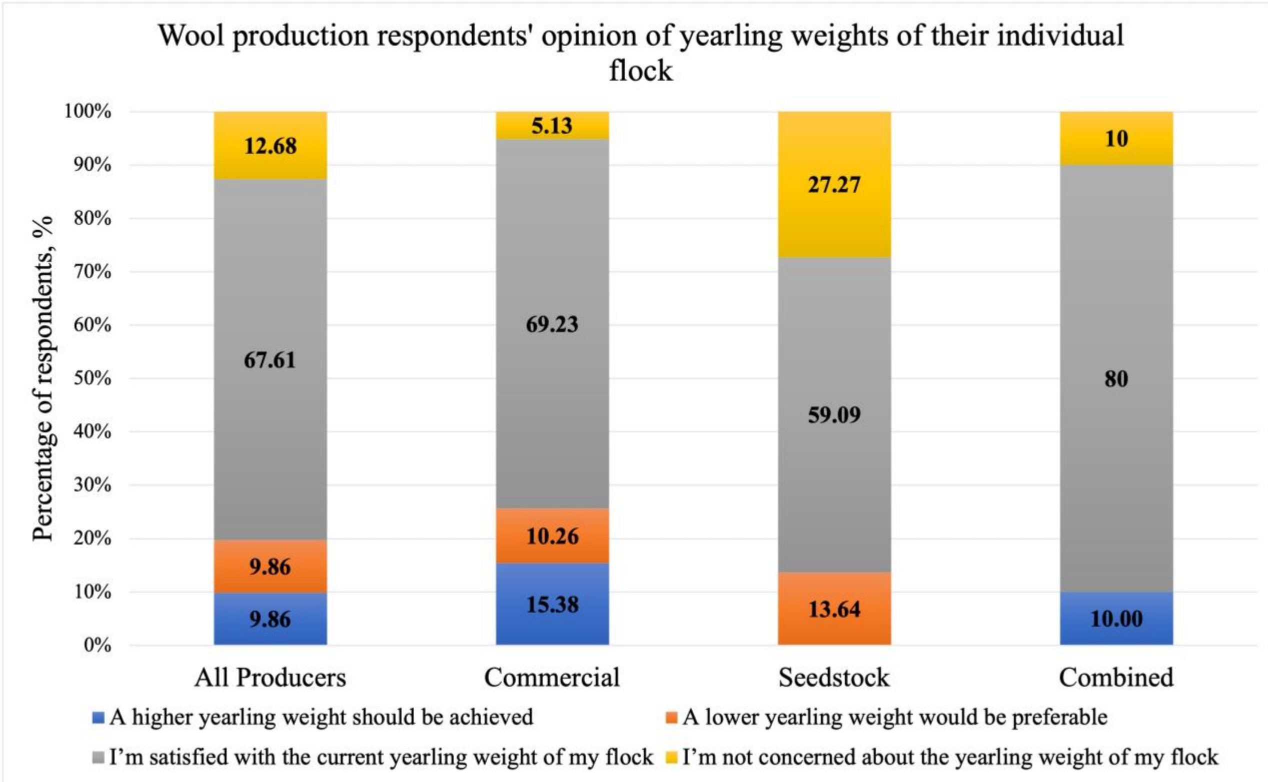

Figure 2.4 Wool production respondents' opinion of the yearling weights of their individual flock

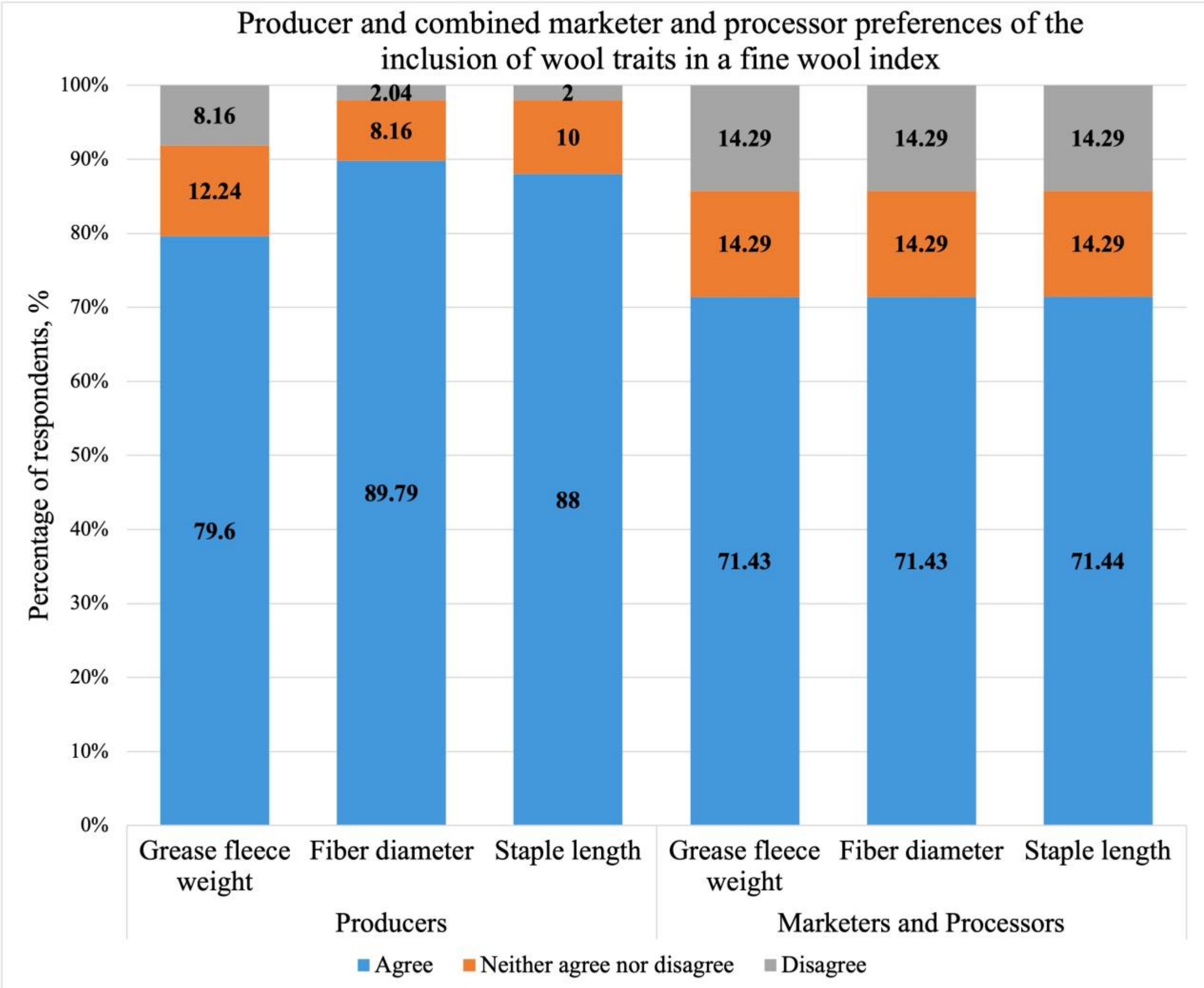

Figure 2.5 Producer and combined marketer and processor preferences of the inclusion of wool traits in a fine wool index

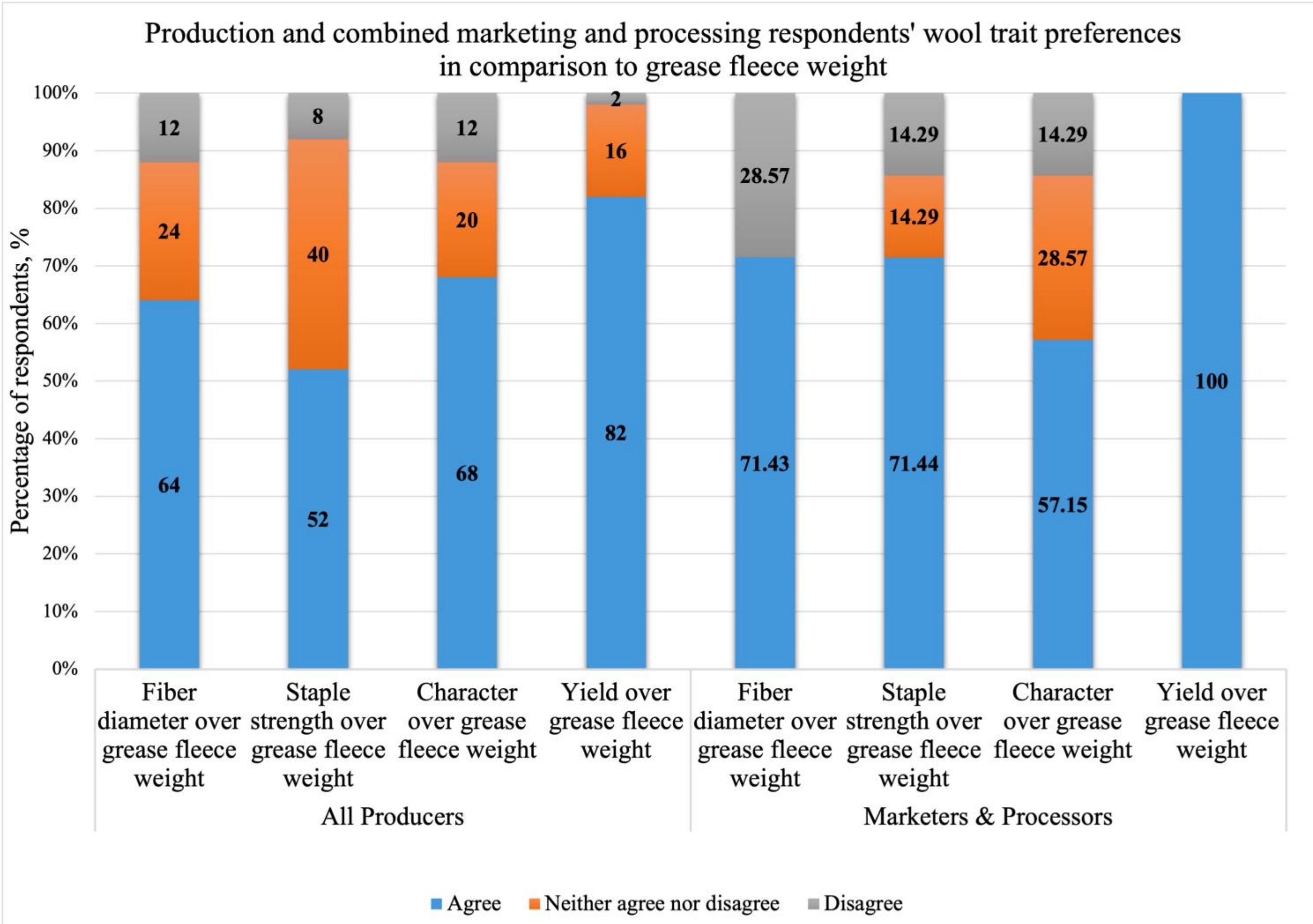

Figure 2.6 Production and combined marketing and processing respondents' wool trait preferences in comparison to grease fleece weight

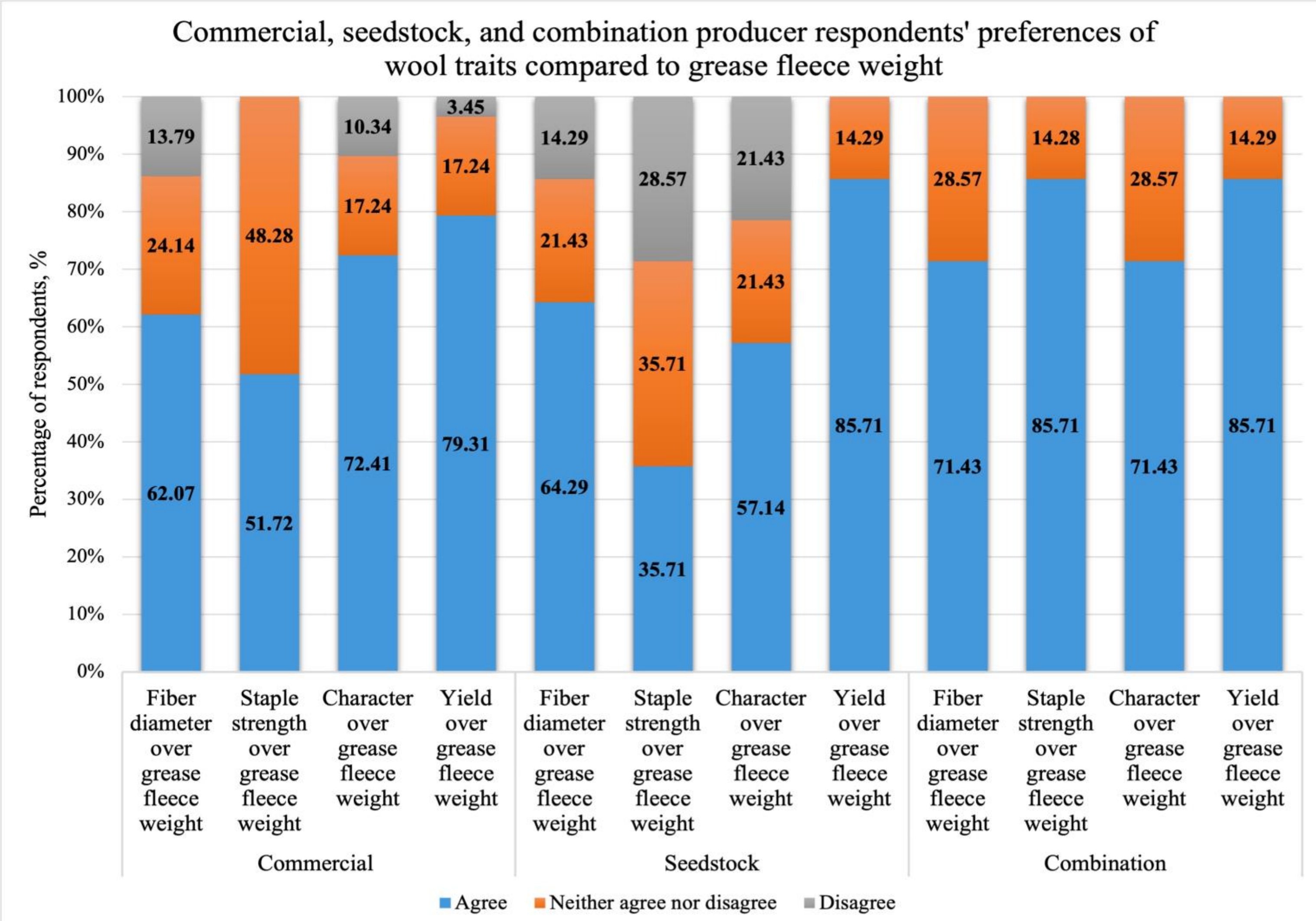

Figure 2.7 Commercial, seedstock, and combination producer respondents' preferences of wool traits compared to grease fleece weight

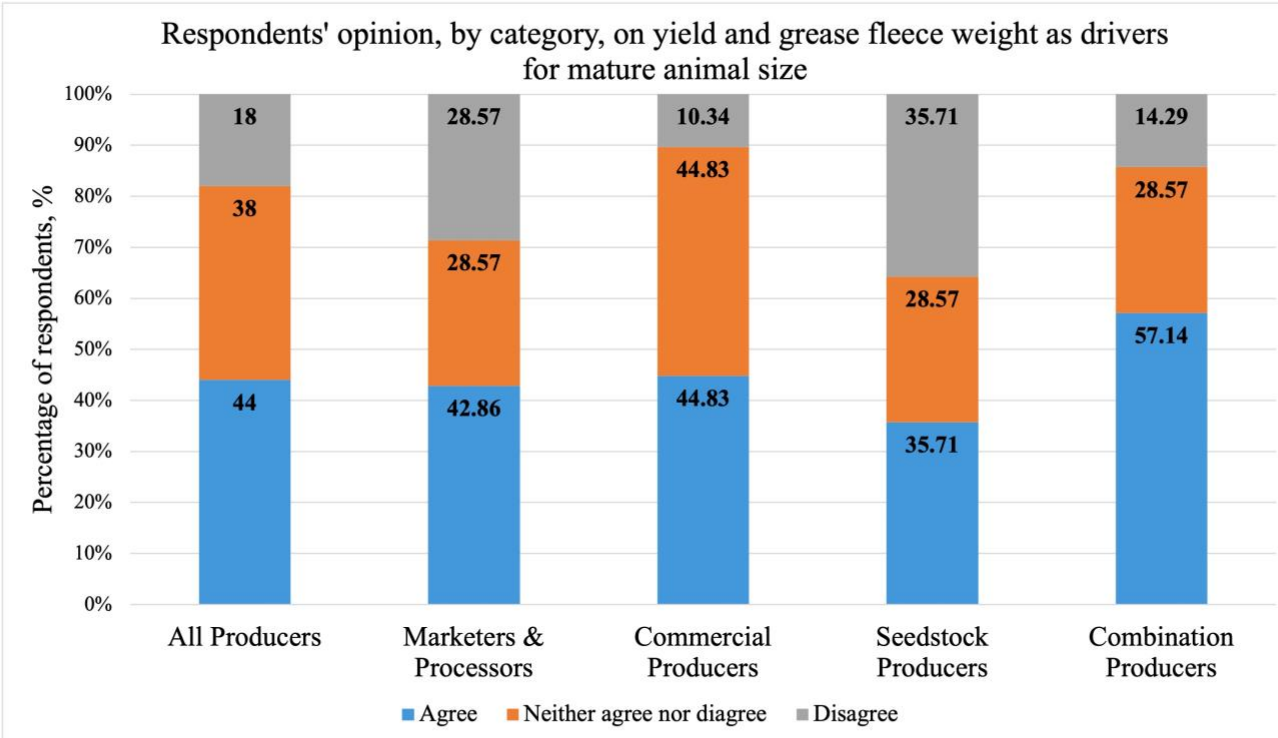

Figure 2.8 Respondents' opinion, by category, on yield and grease fleece weight as drivers for mature animal size

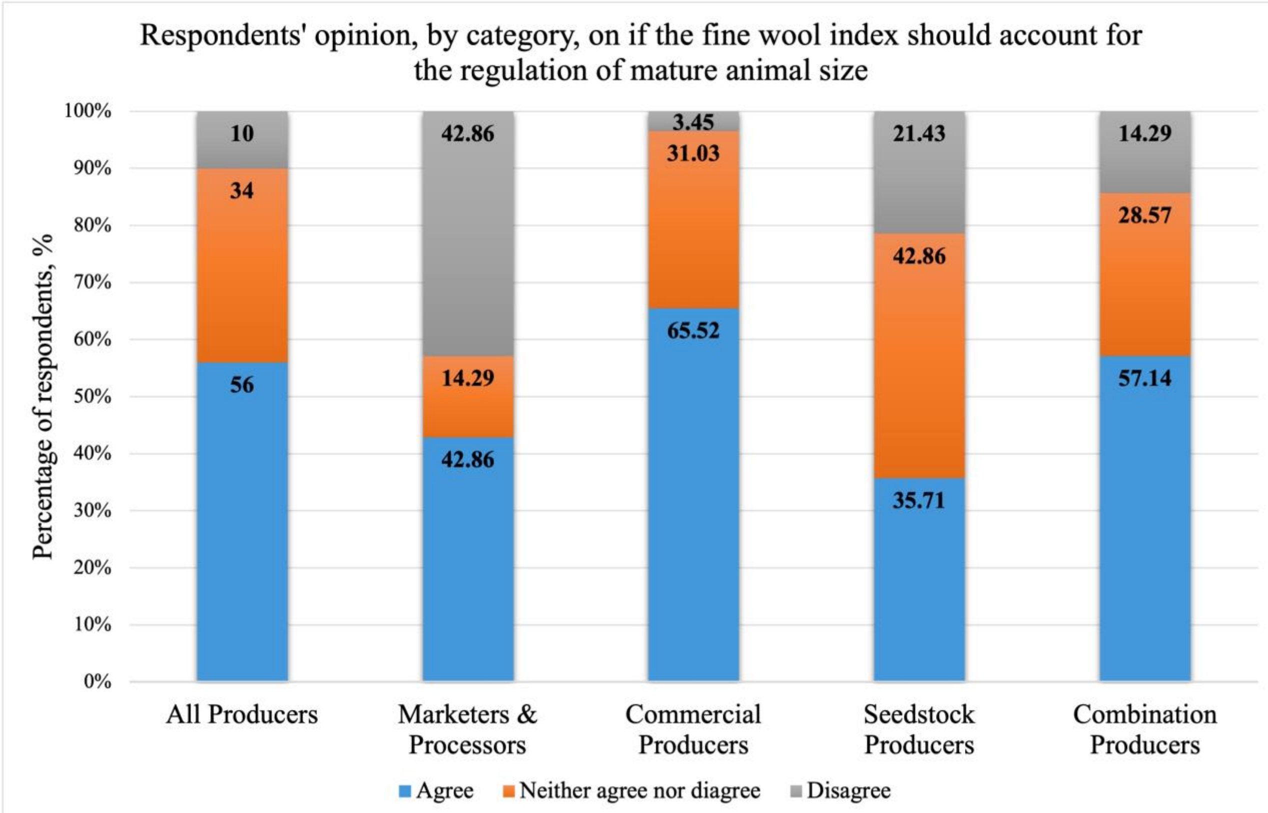

Figure 2.9 Respondents' opinion, by category, on if the fine wool index should account for the regulation of mature animal size

Chapter 3 - Fine Wool Production: Index Development

Introduction

Wool production in the United States (U.S.) has been declining since the 1940s for various reasons, though it was mainly driven by a shift from wool to meat production (Jones, 2004). The repeal of the National Wool Act of 1954, deterioration of U.S. wool processing infrastructure, the advent of synthetic fibers, and increased global competition also contributed to production declines. Despite past and present challenges, the domestic wool industry is in a position of opportunity as new technologies drive product innovation. There is potential for expansion of U.S. wool markets, as new processing markets emerge worldwide, and the U.S. military continues to support American wool. This means stakeholders need to focus on improving fine wool production in order to reap the benefits of these changing markets. Improvement can be made through the implementation of a genetic selection index program focused on fine wool production. The National Sheep Improvement Program (NSIP) provides several genetic selection indices for U.S. commercial sheep production, but those currently available provide little emphasis on wool quality (Notter & Lewis, 2018).

At the end of World War II, demand for military uniforms dropped significantly, leading to fewer orders for wool textiles (Jones, 2004). In response, wool prices started to decrease, and the U.S. sheep industry shifted production from wool to meat. After World War II, the National Wool Act of 1954 was passed to stimulate the U.S. wool industry by providing income support to producers impacted by low wool prices (Anderson et al., 2009). Although the Act delayed further decline for nearly a decade, it could not counter the surge in popularity of more affordable synthetic fibers. By the late 1960s, domestic supply and demand for raw wool had plummeted (Jones, 2004; Anderson et al., 2009). The National Wool Act could no longer sustain

U.S. wool production and prices, which led to its eventual phaseout by President Clinton (Anderson et al., 2009). These factors contributed to the continual deterioration of the domestic wool supply into the late 20th and early 21st centuries, which led to the eventual demise of American wool processing infrastructure (Anderson et al., 2009). By the early 2000s, the near total loss of domestic processing contributed to increased exports of U.S. wool according to the United States Department of Agriculture (USDA-ERS, 2020). A large portion of U.S. exports have been sent to China. However, beginning in 2019, the instability of U.S.-China trade relations and shutdowns from COVID-19 negatively impacted U.S. exports, according to the American Sheep Industry (ASI, 2021). As a result, the ASI began promoting American wool in Western Europe, Mexico, India, and Southeast Asia, where there is an opportunity to expand U.S. wool processing and demand. Aside from new international marketing prospects, there is a growing opportunity on the domestic front.

Since the start of the COVID-19 pandemic, the agricultural industry has seen a shift in consumer decisions. As businesses were closed to 'flatten the curve' and supply chains were disrupted, consumers began relying on more stable, local sources for several products (Hobbs, 2020). If this consumption trend continues, U.S. wool garment businesses such as Duckworth, Ramblers Way, Voormi, and Fishhook socks will be at an advantage, as they strategically market transparent, sustainable, and American-made products (ASI, 2021). There are two major undertakings to reach the full market potential of fine wool: 1) consumer education of the physical properties and advantages of wool, and 2) utilizing wool processing technology, such as the superwash. Overcoming these hurdles would encourage increased garment making, in the form of next-to-skin products, rather than strictly cold weather gear, as well as increase overall demand for wool garments. American wool of similar grade and quality achieves 75-85% of the global prices set by the world's largest wool exporter, Australia (USDA-AMS, 2021). These price reductions are primarily due to market standards, timing, lack of uniformity, and wool purity issues. Despite the challenges the U.S. wool industry faces on the global front, by utilizing a selection index that emphasizes fine wool quality, producers will be more well suited to compete on the international stage.

When the selection of multiple traits is desired, index selection is the most efficient form of genetic selection (Hazel and Lush, 1942). Hazel (1943) described that the construction of selection indices requires information on genetic parameters, phenotypic parameters, and relative economic values (REV) for each index trait to calculate the index weight. If estimated breeding values (EBV) for index traits are available from previous multi-trait genetic analyses, however, the genetic and phenotypic parameters are not needed, as it is possible to use REV to weight the selection index rather than index weights (Schneeberger et al., 1992). The creation of selection indices specifically for fine wool production is not an unfamiliar concept. Australia has utilized selection indices to improve the genetics of the country's wool clip since 2005 (Brown et al., 2007). In 2012, Australia expanded their multi-trait genetic selection programs within the Merino breed by developing six new indices under MERINOSELECT (Brown et al., 2016). These indices may be useful for Australian producers; however, they should not necessarily be used in U.S. fine wool selection as they are based on the Australian Merino population and their economic factors.

Due to different production populations, conditions, and economic situations, it is more impactful to create indices fitted for U.S. conditions; therefore, emphasis has been placed on developing a selection index for the improvement of domestic production flocks. Many U.S. based indices and EBV have been utilized since the establishment of NSIP, with genetic improvement focused on traits influencing prolificacy, growth, and carcass. Borg (2004) developed the Western range index (WRI), the first within NSIP to emphasize wool production. The WRI emphasizes body growth and ewe prolificacy, but also includes grease fleece weight (GFW) and fiber diameter (FD; Notter and Lewis, 2018). Even with the establishment of the WRI, little emphasis of wool production and quality traits has occurred apart from individual EBV estimates. This lack of emphasis has led the Fine Wool Consortium (FWC), a group within NSIP, to strive for greater emphasis on wool quality traits through enhancement of genetic selection tools for U.S. fine wool producers' flocks. The individual wool EBV in NSIP, along with producer preferences through survey methods, can be utilized to develop a fine wool selection index that may increase emphasis of genetic selection on fine wool production. Additionally, developing a fine wool selection index, along with the utilization of other NSIP indices, could give producers the opportunity to achieve balance between production of meat and wool in their flock.

The objectives for this study are as follows: 1) to create a unified breeding objective for the U.S. fine wool industry by estimating the economic value of important wool traits, considering both domestic and international markets, and 2) utilize the resulting economic value estimates and previously analyzed EBV to create a selection index that U.S. fine wool producers can utilize to increase profitability through increased production and improved wool quality.

Materials & Methods

General

The primary focus of this selection index was U.S. fine wool production, a system that comprised breeds of sheep utilized for their ability to produce high-quality fine wool, typically less than 22.05 microns in diameter (Kott, 1993). Though several breeds meet these criteria, researchers were primarily concerned with two breeds which will be described as breed A and breed B to maintain confidentiality. Grease fleece weight had the largest number of observations with 11,872 for breed A and 27,917 for breed B, whereas, curvature (CURV) had the lowest number of observations with 6,009 for breed A and 2,661 for breed B. The descriptive statistics for available NSIP wool phenotypes of breeds A and B were pre-adjusted for fixed effects relevant to each trait, with fleece weights (FW) and staple length (SL) pre-adjusted for birth type, rearing type, and age of dam, FD was also pre-adjusted for birth type. Age at recording was accounted for in all traits. Descriptive statistics for each trait and each breed are described in Table 3.1. The descriptive statistics and a previously conducted survey of fine wool industry stakeholders were referenced as the breeding objective was developed. Initially, GFW, clean fleece weight (CFW), fleece yield (YLD), SL, FD, and fiber diameter coefficient of variation (FDCV) were considered for inclusion in the index based on basic wool grading knowledge and a literature review. After identifying these initial index traits, a survey of industry stakeholders was performed to evaluate prioritization of wool traits, with additional input from industry leaders, such as wool buyers and researchers. As a result of survey evaluation, discussion with industry leaders, and consideration of database limitations, it was decided to include FD, SL, GFW, and FDCV in further development of the fine wool selection index, along with CURV, to incorporate more wool quality traits into the index. All proposed traits had available EBV calculated through the NSIP multi-trait genetic evaluation program.

Economic Values

The next step of index development involved the calculation of an economic value for each trait. This step is critical to index development, as economic values serve as weighting factors for indices that use EBV information instead of phenotypes (hereafter referred to as a genetic index). Once index traits were finalized, various data sources were used to derive preliminary economic values. These data sources included USDA market information, the Australian Wool Exchange Limited (AWEX), and personal communications with American wool buyers and textile producers.

Fiber Diameter

The economic value of FD was developed through the AWEX Southern Market Indicator, which reported historical 5-, 7-, and 10-yr price averages based on microns. The southern market indicator was used, rather than the eastern indicator, based on similarities between the U.S. and Australian markets and its utilization by American wool buyers. With this report, two preliminary economic values for FD were calculated based on 10-yr price averages. Upon initial evaluation, Microsoft Excel (MicrosoftCorp., Redmond, WA) was used to transform the raw price data into two economic values of FD. The prices given were converted from Australian dollars to U.S. dollars at a 10 yr average conversion rate of 0.81. The converted prices were set at 80% of the Australian price to better estimate the value of clean, domestic wool prices (USDA-AMS, 2021). Following the conversion process, the price differences were calculated between each half-micron interval for two ranges, one from 17 microns to 22.5 microns and the other from a narrower range of 20-22.5 microns. An economic value for each range was then calculated by taking the mean of all the half-micron price differences in each range and then doubling them to observe the average change in the value of a single micron increase while other traits remained the same.

Staple Length

Through evaluation of AWEX Premium and Discount reports, it was observed that the distribution of SL economic values was severely nonlinear, with the most economic advantage being found at an intermediate optimum between 80 to 90 millimeters (mm). This observation was confirmed through personal communications with the American wool buyers (R. Powers and J. Bannowsky, personal communication Fall 2021). In cases where the population price distribution may fit a quadratic trend, it is appropriate to apply an economic value based off a linear regression line (Wilton et al., 1968). However, the distribution of SL premiums and discounts was so severely nonlinear that it better fit a polynomial trend, in which a linear regression line would fail to adequately reward those animals within the optimal economic profit range. To evaluate whether SL could be restricted to keep the population mean at an economic optimum or if further calculation was necessary to address the severe nonlinearity of SL, the means of the NSIP breed records for breed A and B were used to determine whether the mean SL was below or within the ideal range between 80 mm and 90 mm. As the A and B breed means for SL were within the optimum range at 88.50 mm and 81.21 mm, respectively, the index was evaluated with complete restriction of SL to keep the breed means within that optimal level.

In a traditional phenotypic index, hereby called a traditional index, trait restriction is applied by augmentation of the phenotypic and genetic (co)variance matrices, which involves a maximized aggregate genotype response while the SL response is limited to zero (Cunningham et al., 1970). Further, the restricted trait's economic value becomes irrelevant when restricted in a traditional index (Yamada et al., 1975). In the case of a genetic index utilizing mixed model equations, however, alternate adjustments must be made to apply trait restriction properly. Restriction of genetic indices are primarily applied through two methods. With either method of genetic index restriction, the economic value has no relevance as either the Best Linear Unbiased Prediction (BLUP) breeding values, or the adjusted index weight of the restricted trait were constrained to zero (Satoh and Furukawa, 1998). The first method, described by Satoh (1998), applied restriction to an index through constraints of the BLUP EBV (restricted BLUP) rather than to the index weightings. In this method, restrictions are applied directly to the mixed model equations, which can be problematic as the computing load is very large (Satoh, 1998). According to Lin (1990), the second method adjusted the index weight to account for the trait restriction rather than the mixed model equations, resulting in a methodology comparable to traditional index restriction. Much like in Schneeberger et al. (1992), this computation method primarily occurs through replacement of the phenotypic (co)variance matrix with the genetic (co)variance matrix to develop adjusted calculations for restricted index weights. With the use of BLUP, the phenotypic (co)variance matrix became irrelevant due to environmental effects being taken into consideration by the mixed model equations (Lin, 1990). Due to the computing power required to calculate a restricted BLUP and the costs of implementation by Sheep Genetics of Australia, the methodology of Lin (1990) and Schneeberger et al. (1992) was followed for the fine wool index.

Grease Fleece Weight

Two preliminary economic weights for GFW were calculated utilizing 10 yr worth of weekly reports from the USDA loan deficiency payment program. From those reports, the effective repayment rate for graded wool was evaluated on a clean basis from the week of November 9th, 2011, to the week of November 10th, 2021. Micron categories analyzed included: less than 18.6, 18.6-19.5, 19.6-20.5, and 20.6-22.0. The means of weekly effective repayment rates for each micron category were obtained before being averaged across micron category to obtain a 10-yr average price. One economic value was obtained using an average of all the micron categories, while the other was obtained using a narrower range of 19.6 to 22 microns. As the calculated prices remained on a CFW basis, an average YLD of the U.S. flock was assumed at 62% based on personal communications with the American wool buyers (R. Powers and J. Bannowsky, personal communication Fall 2021). The estimated YLD was then multiplied by the 10-yr average of both prices to calculate the GFW economic values used to evaluate the fine wool index.

Fiber Diameter Coefficient of Variation and Curvature

Due to a lack of available market information, the valuation of the FDCV and CURV economic values was complex. This evaluation was further complicated as the optimal level of each trait is largely dependent on the desired end textile product, with processing operations that have different specifications required for the FDCV and CURV. Therefore, preliminary economic values of FDCV and CURV were estimated through personal communications with American wool buyers and textile producers. The FDCV and CURV were given small economic weights calculated as an average of the individual price changes due to FDCV and CURV, with FDCV ranging from 17% to 26% and CURV ranging from 40 degrees per millimeter (°/mm) to 100 °/mm (R. Powers and J. Bannowsky, personal communication Fall 2021).

Once all economic values were defined, further testing occurred based on index variants created through the different combinations of the economic values. Four prospective indices were developed for each combination of the economic values (Table 3.2). While the economic values of SL, FDCV, and CURV remained unchanged, GFW and FD were analyzed using two economic values calculated from different micron ranges and were combined in all possible ways to develop four indices. One range focused on micron categories between 19.6-22.5 and <18.6-22, which resulted in smaller weights of 5.75 for GFW and -0.276 for FD, respectively. The other focused on a broader range of micron categories between 20-22.5 and 17-22.5, which resulted in a heavier emphasis of 6.08 for GFW and -0.502 for FD, respectively. Each value will provide the index with a different level of emphasis on the trait; for instance, an index with FD weighted as -0.502 will put heavier emphasis on decreased FD and may push the population towards the finer micron fleeces (19 and up) faster than one with a weight of -0.276. These indices are described later in this chapter as: A) with economic weights of 6.08 for GFW and -0.502 for FD; B) with 6.08 for GFW and -0.276 for FD; C) with 5.75 for GFW and -0.502 for FD; and D) with 5.75 for GFW and -0.276 for FD. For each index, genetic and phenotypic correlations, heritabilities, and phenotypic variances were pulled from the multi-trait analysis used by NSIP to calculate the index coefficients and conduct further analysis to determine a final index for inclusion in the NSIP database.

Index Analysis

To generate the required matrix calculations, index coefficients and accuracies were derived prior to index analysis. Each index was evaluated using three different methods, 1) a sensitivity analysis of the economic values, 2) Spearman rank correlations (SRC) between the original WRI and the proposed indices, and 3) SRC between the index values calculated with economic value iterations that are ± 50% of the proposed economic value to further evaluate the sensitivity of the index to changes in economic values. Each analysis was performed in R Studio (Version 1.3.1073, RStudio PBC. Boston, MA).

Selection index coefficients

In traditional indices, the selection coefficients are typically formulated using

Equation 3.1) Index weight estimation

$$P^{-1}Gv = b$$

where, P represents a n x n matrix of phenotypic (co)variances between the traits evaluated and available as the selection criteria, G is a n x m matrix of genetic (co)variances for all m traits, v is the vector of economic values for all objective traits, and b represents the relative index weights

(MacNeil et al., 1997). To evaluate genetic indices that use mixed model equations, however, index coefficients needed to be estimated and applied to EBV calculations. Adjustments to coefficient calculations were applied through the replacement of P based on Schneeberger et al. (1992)

Equation 3.2) Index coefficient estimation for a genetic index

$$b = G_{11}^{-1} G_{12} v$$

where G_{11} is the matrix of genetic (co)variances among the selection criteria, and G_{12} is the matrix of genetic (co)variances among the selection criteria traits and objective traits. In this study, however, G_{11} and G_{12} were identical because the selection criteria and breeding objective consisted of the same traits. The replacement of P occurred because the environmental effects were addressed through BLUP calculations, and thus, did not need to be addressed by the phenotypic (co)variances. Following the replacement of P, SL was restricted through the introduction of LaGrange multipliers by the augmentation of G_{11} and G_{12}, according to Cunningham et al. (1970). Through the augmentation, G_{11} became a 6x6 restricted matrix ${G_{11}}^{*}$ and G_{12} became a 6x5 restricted matrix ${G_{12}}^{*}$, with the augmented restriction recognized by the Asterix. The validity of this method was confirmed through calculation of identical coefficients, according to Lin (1990), which calculated the index coefficient of the restricted trait

Equation 3.3) Restricted index coefficient

$$b_r = [I - G^{-1} G_r{}' (G_r G^{-1} G_r')^{-1} G_r] v$$

where b_r is the restricted traits index weight, I is the identity matrix, and G_r is a row wise submatrix of G from the restricted trait. Once the SL index coefficient was properly restricted, the index coefficients calculated were used to evaluate the index accuracy, index sensitivity to changes in economic values, and rank correlations.

Selection index accuracy

As in the calculation of index coefficients, the substitution of G for P and the restriction was also applied to the calculation of genetic index accuracy. The accuracy calculation of a genetic index is as follows

Equation 3.4) Genetic index accuracy

$$r_{HI} = \frac{b^{*\prime}G_{12}^{*}v}{\sqrt{(b^{*\prime}G_{11}^{*}b^{*})(v'Cv)}}$$

where C represents the *m* x *m* genetic (co)variance matrix among objective traits, $b\,'G_{12}^{*}v$ is the covariance between the index and aggregate genotype, $b'G_{11}^{*}b$ is the index variance, and $v'Cv$ is the aggregate genotype variance (Ochsner et al., 2017). The replacement of P with G_{11}^{*} enables a theoretical prediction of genetic index accuracy, but it also assumes that the G among selection criteria is known without error. In practice, genetic index accuracy is overestimated as EBV estimates cannot be known with complete accuracy due to the residual variances' heterogeneity. The true accuracy of the genetic index is expected to be somewhere between the genetic index and that of a traditional index, calculated with the phenotypic (co)variance matrix (Fozi et al., 2007; Ochsner et al., 2017). The traditional index has a lower calculated accuracy because pedigree information is not accounted for. The calculation of the traditional index is like Equation 3.4, but utilized P rather than the substituted G_{11}^{*}

Equation 3.5) Traditional index accuracy

$$r_{HI} = \frac{b^{*\prime}G^{*}v}{\sqrt{(b^{*\prime}P^{*}b^{*})(v'Cv)}}$$

where $b'Pb$ is the traditional index variance. The traditional and genetic index accuracies were calculated to offer a range in which the true accuracy may fall. Both calculations were applied to each index in R Studio.

Sensitivity analysis

Economic values are rarely known with absolute certainty, so a sensitivity analysis was undertaken to evaluate the robustness of each index to errors or changes in economic values. In this case, the sensitivity evaluation was conducted through observed changes in each index's efficiency as a result of changing economic values. The efficiency calculation assumed that there were “used” index coefficients and economic values based on the iterations from “true” index coefficients and economic values assumed to be at an optimum. The efficiency is calculated as

Equation 3.6) Efficiency calculation

$$E_u = \frac{\left[\frac{b_u^{*\prime} G_{12}^* v_t}{\sqrt{b_u^{*\prime} G_{11}^* b_u^*}}\right]}{\sqrt{b_t^{*\prime} G_{12}^* v_t}}$$

where b_u^* is the index coefficient of the “used” value, b_t is the index coefficient of the “true” value, v_t is the economic weight of the “true” value, and E_u is the efficiency of the values tested (Schneeberger et al., 1992; Ochsner et al., 2017). The "true" economic value was assumed to be the proposed economic values calculated through the data sources described earlier, and the "used" were the economic value iterations tested. Therefore, the efficiency calculated was a percentage measure of how efficient the “used” index and was compared to the “perfect” index where the “used” and “true” economic values were identical with 100% efficiency. Losses of efficiency were evaluated by subtracting the percentage of efficiency by 100%, or the “perfect” index. Like Ochsner et al. (2017), the sensitivity was tested individually for each trait in each index by iterating "used" values at ± 50% of each trait's proposed "true" economic value. For instance, an index with a "true" GFW economic value of 6.08 was tested for "used" values between 3.04 and 9.12, while an index with a "true" CURV economic value of 0.0042 was tested for "used" values between 0.0021 to 0.0063. Genetic (co)variance matrix and the other economic values were held constant while each iteration was tested.

Spearman rank correlations

Spearman rank correlations were used to assess individual rank changes between the WRI and the four proposed indices. The SRC were also evaluated between economic value iterations and the proposed economic values of each trait in each index to further investigate the impact that changes in economic values would have on the selection index rankings. The SRC testing was applied using the restricted index coefficients calculated following the procedures in Schneeberger et al. (1992) and using the EBV of 14,501 individuals within the top 10% of WRI values in the NSIP database (Table 3.3). The top 10% of WRI values were used as industry producers have greater interest in high preforming animals that are candidates for selection in nucleus herds, to minimize the number of inactive animals evaluated, and to maximize the fine wool index trait EBV that were reported for each. Similar to efficiency testing, the SRC evaluation used iterations that were ± 50% from the proposed economic value to evaluate the effects that changing economic values would have on the amount of reranking that occurred, both between the index created in this study and the WRI and reranking that would occur directly as a result of inaccuracies in the economic values. For instance, the GFW economic value of 6.08 was tested with iterations between 3.04 and 9.12, in which each iteration was tested for reranking between the WRI and between the other economic values tested.

Results & Discussion

Economic values

The preliminary economic value, genetic SD, and REV of each trait in each index tested are summarized in Table 3.2. The economic values -0.039, 0.0042, and 0 for FDCV, CURV, and

SL, respectively, were the same for each index. The economic values of GFW and FD, however, were varied based on the micron range used for calculation. Economic values with a heavier emphasis based on a wider micron range were 6.08 for GFW and -0.502 for FD, whereas the smaller weights based on a narrower micron range were 5.75 for GFW and -0.276 for FD.

Fiber diameter and fiber diameter coefficient of variation

The FD and FDCV economic values were negative, which was expected, as the price for wool generally decreased as the micron and variability increased (Wood, 2003). Ponzoni (1988), Mortimer et al. (2010), and Notter and Lewis (2018) supported the negative sign for the FD economic value, though the values were different from those tested in this study. The value differences are not concerning, however, as they are likely a result of breed, region, shifts in demand, and differences in future condition estimation (Hazel, 1943). In comparison, relatively few economic value estimates of FDCV were found in the literature. One example found was Purvis and Swan (1999), which estimated FDCV economic values when the authors attempted to incorporate style into Merino breeding objectives. The FDCV was calculated as 20% of the FD economic value, approximately 10% of the CFW price of $9.00. The approximation by Purvis and Swan (1999) was slightly different from the economic value utilized in this study, as the economic value of FDCV was approximately 8% and 14% of the FD values -0.502 and -0.276 tested, respectively. The economic value of FDCV estimated by Purvis and Swan (1999) was ultimately larger than that estimated for the U.S. fine wool index. Comparing the two studies should be done with caution, however, as the 1999 study was based on a very different production level and geographical region, namely superfine flocks with a mean FD between 17.5 and 17.9 microns in the New England area of Australia.

Curvature and grease fleece weight

Economic values for CURV and GFW were positive, although CURV had a much smaller magnitude. Like FDCV, there has been little available market information, and economic value estimation of CURV reported. This is likely because the optimal fiber CURV largely depends on the desired end-product attributes, and the optimal CURV range may differ from processor to processor. In some instances, such as knitwear production, higher CURV is more desirable due to the production of bulkier, warmer, and softer fabrics (SGS, 2011). Once wool FD becomes finer than 19.5 microns, higher CURV than average may be associated with lower spinning performance. In a sensory evaluation completed by McGregor et al. (2015), however, knitted wool fabrics from high CURV superfine wool (17 microns) were preferred by respondents for breathability, comfort, moisture-wicking capabilities, and skin feel compared to fabrics made of low CURV wool. After personal communications with the American wool buyers, CURV was included in the fine wool index at a very small but still positive economic weight of 0.0042, which may result in small, slow increases in CURV.

The economic values of GFW, unlike CURV, were much larger. Borg (2004) produced similarly positive estimates of GFW economic values relative to the additive SD but were much smaller than the GFW REV observed in this fine wool index (Table 3.2). While the Borg (2004) index evaluated GFW REV that ranged from 0.046 to 0.214, this study evaluated GFW REV of 2.125 for indices A and B and 2.009 for indices C and D with economic values of 6.08 and 5.75, respectively. It is likely that the larger estimates of this studies index are due to the major emphasis on fine wool rather than growth and reproduction traits (Borg, 2004). Additionally, wool value has changed drastically since 2004 with prices raising from an average of 0.80 cents per pound to $1.70 per pound in 2021 (USDA-NASS, 2005, 2022).

Staple length

Unlike the other traits, the economic value of SL was placed at zero as the value was unrelated to calculations. The lack of impact on calculations is largely due to the restriction of SL in the index, which occurs through the augmentation of G^*_{11} and G^*_{12}. The restriction renders the SL economic value irrelevant by making the index weights and response to selection independent of the economic value of SL (Gibson and Kennedy, 1990; Satoh and Furukawa, 1998). This augmentation allowed for the calculation of non-zero index coefficients for SL that were dependent on the parameters and economic weights of the other traits included in the index.

Index coefficients and calculations

Index coefficients

The index coefficients estimated were slightly different for each of the four indices tested. Like Lin (1990) and Schneeberger et al. (1992), each of the index coefficients were identical to the economic values applied above, apart from SL and the LaGrange multiplier (Table 3.4). The average SL coefficient value of the four indices was -0.089, with individual values of -0.088, -0.097, -0.082, and -0.091 for indices A, B, C, and D, respectively. According to Lin (1990), these adjusted economic values satisfy the complete restriction of SL without requiring the adjustment of the multitrait mixed model equations through BLUP. These index coefficients acted as the weighting factors of the four indices and were used to evaluate the accuracy of the index, sensitivity testing, and SRC.

Index Accuracy

The accuracy of four indices with alternate economic weights were evaluated through restricted traditional and restricted genetic index calculations to estimate the range of the possible accuracies, similar to Ochsner et al. (2017). In a genetic index, the replacement of P

with G_{11}^{*} enables a theoretical prediction of genetic index accuracy, but it also assumes that the G among selection criteria is known without error. In practice, genetic index accuracy is overestimated as EBV estimates cannot be known with complete accuracy due to the residual variances' heterogeneity. The true accuracy of the genetic index is expected to be somewhere between the genetic index and that of a traditional index, calculated with the phenotypic (co)variance matrix (Fozi et al., 2007; Ochsner et al., 2017). The genetic accuracies were split with an accuracy of 0.92 for indices A and C and 0.91 for indices B and D, similarly there was a slight variation in the traditional index accuracies. The largest traditional accuracies observed were 0.60 for index B, which had the stronger weighting of GFW (6.08), and D, which had the weaker weighting of GFW (5.75). Both indices had a weaker weighting of FD (-0.276). In contrast, indices A and C had slightly weaker traditional index accuracies reported at 0.58, and both had a stronger economic weight for FD (-0.502). According to these estimates, any of the four indices selected for application will likely have an accuracy between 0.58 and 0.91.

The traditional accuracy of each index is much lower than that of the genetic index due to the absence of relationship information, while in the genetic index, pedigree information is accounted for in BLUP calculations (Schneeberger et al., 1992; Bourdon, 1998). Although genetic indices have increased selection accuracy compared to traditional indices, they tend to be overestimated due to the assumption that the genetic (co)variance matrix among selection criteria is known perfectly (Ochsner et al., 2017). Therefore, the traditional index accuracy and the genetic accuracy were both evaluated.

Fozi et al. (2007) estimated the accuracies of four genetic indices in Merino sheep that included different combinations of body weight (BW), reproductive, wool, and wool follicle measurements at four different micron premiums (3%, 6%, 12%, and 20%) and different ages from one to five. The accuracies ranged from 0.369 to 0.910. The lower accuracy came from the lowest micron premium at 1 yr of age, whereas the larger accuracy came from the highest micron premium at 4 and 5 yr of age. The accuracy estimates of the four U.S. fine wool indices tested were closer to the upper accuracy estimates reported in Fozi et al. (2007) and had a narrower accuracy range between the four indices. The larger range of accuracies in the Australian Merino study was likely due to the use of different age classes and combinations of traits, whereas the four U.S. fine wool indices varied only according to the fluctuations in the economic values.

According to these results, the minimum accuracy attained through the selection of these indices was 0.58 for index A, 0.60 for index B, 0.58 for index C, and 0.60 for index D. Differences in traditional index accuracies between the four indices were likely due to the varied emphasis on FD, though, the narrow variation was likely due to the use of the same traits for each index. For each index evaluated, some of the base calculations (i.e., $b'Gv$ and $b'Gb$) used to evaluate the genetic index accuracy were used to calculate index efficiencies.

Sensitivity analysis

Tested at ± 50% of the proposed economic value for each index, the majority of changes in economic values resulted in less than a 1.5% loss of efficiency (Table 3.5). The maximum loss of efficiency was 0.064 and occurred in index C when the economic value of GFW was reduced by 50% from 5.75. In contrast, the minimum loss of efficiency was 0.0000184 and occurred in index B when CURV was increased by 50%. Consistently across each trait and index, the reduction in efficiency was larger when the economic value was reduced by 50%. According to Vandepitte and Hazel (1977), though, the underestimation of economic values was more critical to the efficiency of an index than the overestimation.

Across all indices and traits, the larger efficiency losses were consistently observed in GFW, while the smaller losses were consistently observed in CURV. According to Amer et al. (1998), this trend was likely driven by the weighting of economic importance since traits with lower economic importance tended to be more robust to changes in economic values and resulted in minor efficiency losses. The SL economic value was an exception to these trends, as the SL economic value was 100% efficient in each index and iteration tested. The perfect efficiency assumed by SL was primarily due to the restriction of G_{11}^{*} and G_{12}^{*}, which made the economic weight independent of the response to selection and index weights (Gibson and Kennedy, 1990; Satoh and Furukawa, 1998).

The results of all four indices suggest that they are relatively insensitive to changes in economic values. The only two exceptions were the 0.057 and 0.064 efficiency losses in indices A and C, respectively, when the economic values were underestimated by 50% of the 'true' economic value tested. Even so, the majority of results were supported by Vandepitte and Hazel (1977), which assessed errors of ± 50% in economic values and observed a total reduction in genetic gain of less than 1% in all case. The findings indicate that any of the four indices chosen for the NSIP database can be relied upon regardless of the fluctuating economic conditions or uncertainties in economic values.

Spearman rank correlations

Spearman rank correlations were used to determine the amount of reranking between animals using the WRI and each proposed fine wool index, as well as reranking that occurred between each index when different variations of the economic values were used (i.e., ± 50% of 6.08 for GFW in index A). For instance, the correlation between animal ranking was tested for index A outcomes using economic value variations for GFW of ± 50% of 6.08. Estimated breeding values were used from a dataset that contained 14,501 animals within the top 10% WRI values in the NSIP database. The correlations between the fine wool indices and the WRI were consistent across each proposed fine wool index, with mean correlations of 0.28 for each index (Table 3.6). In each index, the amount of reranking that occurred between iterations of each trait was negligible since differences were only observed after the second decimal. The results of the rank correlations between the WRI and the proposed fine wool indices indicated that a large amount of animal reranking may occur between the WRI and any of the four indices evaluated. Likely, the low correlations between the WRI and each proposed fine wool index were due to the differences in the trait inclusion of each index. While each proposed fine wool index placed significant emphasis on increased wool production and quality, the WRI was focused largely on early growth and ewe prolificacy with only a minor emphasis on GFW and FD (Notter and Lewis, 2018). The GFW and FD are the only traits in common between the WRI and the fine wool indices, which indicated that the (co)variance matrices used in the calculation were largely different.

The SRC between each index value calculated from different economic value iterations for each trait in each index resulted in consistently high correlation values. The lowest correlation that occurred was 99.989%, which was observed for GFW in index C. These results suggested that very little reranking will occur between animals for any of the four indices, even if errors or changes in the economic values occurred at ± 50% of the proposed value. Even stronger than the sensitivity results, these results confirmed that each of the four indices was robust to changes in economic values.

The proposed fine wool index

Considering the results of robustness to changes in economic values for all four indices, the selection index proposed for inclusion in the NSIP database was represented as

Equation 3.7) The fine wool selection index

$$H = (6.08 * EBV_{GFW} - 0.502 * EBV_{FD} - 0.088 * EBV_{SL} - 0.039 * EBV_{FDCV} + 0.0042 * EBV_{CURV})$$

where EBV_i is represented by the EBV of each trait from the NSIP database. This index, calculated through the economic values represented in index A, was chosen based on the idea that a heavier weighting of GFW and FD would provide producers with a faster, more aggressive approach to increase GFW and decrease FD. Aggressive improvement was desired, as GFW and FD improvements would increase economic returns down the wool supply line. Fiber diameter and GFW are economically relevant, as FD drives wool pricing (Iman et al., 1992), and increased GFW will lead to increased product if managed properly during production (Johnson and Larsen, 1978). Indirectly, increased GFW may also increase supply for marketers and processors, as GFW can lead to increased CFW due to the high correlations between the two (Swan et al., 1995).

Though not chosen for inclusion in the NSIP database, index B may be preferable in some industry scenarios due to the slower, less aggressive improvement of FD. While decreased FD should increase economic returns, there is also a global market for 20-to-23-micron wool which the major wool producing countries cannot meet due to the primary production of fiber either above 19 microns or below 23 microns (ASI, 2021). The U.S. market currently fits this niche, which could mean improved sales opportunities for American wool in the future if this market is not met elsewhere. In addition, the more aggressive approach of index A will likely push the NSIP fine wool population towards microns below 19.5 more quickly than an index with lower FD emphasis. Once the majority of the U.S. fine wool population is above 19.5 microns, the industry runs the risk of entering into direct competition with Australia, which could potentially reduce demand for U.S. wool. The less aggressive approach to FD improvement addresses these concerns and indicates that selection using index B may keep the U.S. fine wool population within the 20-to-23-micron range for a longer period of time than index A. Though this index was not chosen for inclusion in the NSIP database, it is important to understand the potential implications of a less aggressive approach to selection for FD.

The biggest limitation to the U.S. fine wool index (index A) includes the lack of BW trait inclusion. As GFW is increased through selection based on the index, likely, BW traits will also be increased due to positive correlations between the two (Borg et al., 2007). Therefore, to maintain control of BW, it will be important to select replacements using an EBV for BW, such as yearling weight (YWT) or weaning weight (WWT), in addition to the fine wool index. As future development of the fine wool index occurs, the BW limitation may be accounted for through the inclusion of BW. Additionally, it may also be beneficial to add CFW to the fine wool index to select for increased FW more directly. As future development occurs and the U.S. fine wool population means change with selection, it may also be beneficial to account for the nonlinearity of SL if the population begins to move out of the economic optimum. In the next 5 yr, as the index evolves through new development, markets shift domestically and abroad, and new information is accumulated, it will be necessary to reassess the population means and economic values of all traits utilized.

Conclusion

Results of the sensitivity and SRC testing indicated that any of the four indices should be robust to normal economic fluctuations and useful in improving wool production, quality, and profitability. Due to these results, the selection index proposed for inclusion in the NSIP database was based on index A and was presented with index weights of 6.08, -0.502, -0.088, -0.039, and 0.0042 for GFW, FD, SL, FDCV, and CURV, respectively. The expected outcomes from the utilization of this selection index included increased production quantity and improved wool quality. Additionally, when used in conjunction with proper management, U.S. fine wool producers may increase their profitability. Besides the expected increase in GFW and decrease in FD, this fine wool index may reduce the FDCV and increase the CURV slowly. Due to these traits' relatively low index weights, they may exhibit a very small or negligible response to selection over a short period of time. Furthermore, due to the restrictions applied to the SL index weighting, SL is likely to remain constant since the response to selection is limited to zero.

Through the proper uptake and use of this index, U.S. wool producers may experience increased production and quality over time. Increased production and quality of U.S. fine wool over time may lead to increased profitability and thus may increase the competition for U.S. fine wool domestically and abroad. However, this is largely dependent on the uptake of the index, future evaluation to make sure that the index continues to meet the needs of the NSIP fine wool population, and further research towards optimal selection outcomes. Future research efforts should be focused on meeting the shortcomings of this fine wool selection index. These include: 1) The economic value assessment of BW traits to include the influences of wool traits, 2) The evaluation of the economic nonlinearity in SL to optimize selection towards the intermediate range between 80 and 90 mm, 3) The exploration of more time- and cost-effective means of evaluating CFW and YLD, and 4) The assessment of CFW or YLD for inclusion into NSIP as an EBV within the fine wool index.

Even though limitations and future research are needed to further optimize fine wool selection, the U.S. fine wool index developed may be utilized to increase fine wool production and quality, with emphasis on GFW and FD. The fine wool selection index may also provide stakeholders with a unified breeding objective, which can theoretically be used to produce a more uniform fine wool sheep population. However, due to the wide range of breeding goals among U.S. operations, the success of the U.S. fine wool index and breeding objective will depend on producer adoption and proper management of the wool clip.

References

Amer, P. R., R. Crump, and G. Simm. 1998. A terminal sire selection index for UK beef cattle. Anim. Sci. 67:445-454. doi: https://doi.org/10.1017/S1357729800032859

ASI. 2021. Wool trust report 2019-20. USDA-NASS. Washington, D.C. Available from: https://www.ams.usda.gov/reports/wool-trust (Accessed 20 March 2021.)

Anderson, D. P., O. Capps, E. E. Davis, and S. D. Teichelman. 2009. Wool price differences by preparation in the United States. Sheep Goat Res. J. 24:1-9.

Borg, R. C., D. R. Notter, L. A. Kuehn, and R. W. Kott. 2007. Breeding objectives for Targhee sheep. J. Anim. Sci. 85:2815-2829. doi: https://doi.org/10.2527/jas.2006-064

Borg, R. C. 2004. Breeding objectives for Targhee sheep. MS Thesis. Virginia Polytechnic Institute and State Univ., Blacksburg.

Bourdon, R. M. 1998. Shortcomings of current genetic evaluation systems. J. Anim. Sci. 76:2308-2323. doi: https://doi.org/10.2527/1998.7692308x

Brown, D. J., A. E. Huisman, A. A. Swan, H. U. Graser, R. R. Woolaston, A. J. Ball, K. D. Atkins, and R. G. Banks. 2007. Genetic evaluation for the Australian sheep industry. Proc. Assoc. Advmt. Anim. Breed. Genet. 17:187-194. Available from: https://www.academia.edu/download/43450546/Genetic_evaluation_for_the_Australian_sh20160307-9576-wlntey.pdf (Accessed 13 June 2021.)

Brown, D., A. Swan, K. Bunter, A. McMillan, and R. Banks. 2016. Genetic evaluation for the Australian sheep industry: Better targeted and faster genetic gain. Meat and Livestock Australia Limited. North Sydney, NSW. Available from: https://www.mla.com.au/contentassets/ff67f09c82af402fab4b7951ce982322/b.sgn.0127_final_report_.pdf (Accessed 15 March 2021.)

Cunningham, E. P., R. A. Moen, and T. Gjedrem. 1970. Restriction of selection indexes. Biometrics. 26:67-74. Available from: https://www.jstor.org/stable/2529045 (Accessed 20 February 2020).

Fozi, M. A., J. H. J. Van der Werf, and A. A. Swan. 2007. Inclusion of skin follicle traits in selection indices in breeding programs improves genetic gain in Australian fine-wool Merinos. Aust. J. Agric. Res. 58:921-927. doi: 10.1071/AR06347

Gibson, J. P. and B. W. Kennedy. 1990. The use of constrained selection indexes in breeding for economic merit. 80:801-805. doi: https://doi.org/10.1007/BF00224195

Hazel, L. N. and J. L. Lush. 1942. The efficiency of three methods of selection. J. Hered. 33: 393-399.

Hazel, L. N. 1943. The genetic basis for constructing selection indexes. Genetics. 28:476-490.

Hobbs, J. E. 2020. Food supply chains during the COVID-19 pandemic. Cand. J. Agr. Econ. 68: 171-176. doi: 10.1111/cjag.12237

Iman, N. Y., C. L. Johnson, W. C. Russell, and R. H. Stobart. 1992. Estimation of genetic parameters for wool fiber diameter measures. J. Anim. Sci. 70:(4)1110-1115. doi: https://doi.org/10.2527/1992.7041110x

Johnson, C. L. and S. A. Larsen. 1978. Clean wool determination of individual fleeces. J. Anim. Sci. 47:41-45. doi: https://doi.org/10.2527/jas1978.47141x

Jones, K. G. 2004. Trends in the U.S. sheep industry. Econ. Res. Serv., USDA. Agric. Inf. Bull. No. 787. Washington, D.C. doi: 10.22004/ag.econ.33681

Kott, R. W. 1993. Wool grading. Montguide. Bozeman, MT. p. 1- 4. Available from: https://pdf4pro.com/cdn/montguide-msu-extension-534fd9.pdf (Accessed 25 May 2021.)

Lin, C. Y. 1990. A unified procedure of computing restricted best linear unbiased prediction and restricted selection index. J. Anim. Breed. Genet. 107:311-316. doi: 10.1111/j.1439-0388.1990.tb00040.x

MacNeil M. D., R. A. Nugent, and W. M. Snelling. 1997. Breeding for profit: an introduction to selection index concepts. Range Beef Cow Symposium. 142. Available from: https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1141&context=rangebeefcowsymp (Accessed 15 November 2019.)

McGregor, B. A., A. Doughty, J. Thompson, M. Naebe, and D. Tester. 2015. Effects of variation in wool fiber curvature and yarn hairiness on sensorial assessment of knitted fabrics. Text. Res. J. 85(11):1153-1166. doi: 10.1177/0040517514566112

Mortimer, S. I., K. D. Atkins, S. J. Semple, and N. M. Fogarty. 2010. Predicted responses in Merino sheep from selection combining visually assessed and measured traits. Anim. Prod. Sci. 50:976-982. doi: https://doi.org/10.1071/AN10085

Notter, D. R. and R. M. Lewis. 2018. NSIP EBV notebook. Retrieved from: http://nsip.org/wp-content/uploads/2019/01/NSIP-EBV-Descriptions-Update-16-Dec-2018.pdf. (Accessed 22 January 2020.)

Ochsner, K. P., M. D. MacNeil, R. M. Lewis, and M. L. Spangler. 2017. Economic selection index development for Beefmaster cattle II: General-purpose breeding objective. J. Anim. Sci. 95:1913-1920. doi: 10.2527/jas2016.1232

Ponzoni, R. W. 1988. The derivation of economic values combining income and expense in different ways: an example with Australian Merino sheep. J. Anim. Breed. Genet. 105:143-153. doi: https://doi.org/10.1111/j.1439-0388.1988.tb00284.x

Purvis, I. W. and A. A. Swan. 1999. Incorporating assessed style, length, and strength into breeding objectives for fine and superfine Merino flocks. Proc. Assoc. Advmt. Anim. Breed. Genet. 13:177-180. Available from: http://www.aaabg.org/livestocklibrary/1999/AB99037.pdf (Accessed 14 February 2022).

Satoh, M. 1998. A simple method of computing restricted best linear unbiased prediction of breeding values. Genet. Sel. Evol. 30:89-101. doi: 10.1186/1297-9686-30-2-89

Satoh, M. and T. Furukawa. 1998. A method of computing best linear unbiased prediction of aggregate breeding values with the change in some traits restricted to zero. Anim. Sci. Technol. (Jpn.) 69(2):117-122. Available from: https://scholar.archive.org/work/aczqbvp3r5e5hglz3tm4eevtde/access/wayback/https://www.jstage.jst.go.jp/article/chikusan1924/69/2/69_2_117/_pdf (Accessed 10 February 2022).

Schneeberger, M., S. A. Barwick, G. H. Crow, and K. Hammond. 1992. Economic indices using breeding values predicted by BLUP. J. Anim. Breed. Genet. 109:180-187. doi: https://doi.org/10.1111/j.1439-0388.1992.tb00395.x

SGS. 2011. Curvature. Wellington, New Zealand. SGS Wool Testing Services. Available from: https://www.sgs.co.nz/-/media/local/new-zealand/documents/technical-documents/technical-bulletins/wool-testing-info-bulletins/sgs-agri-fibre-curvature-a4-en-11-v2.pdf (Accessed 19 May 2021.)

Swan, A. A., J. Lax, and I. W. Purvis. 1995. Genetic variation in objectively measured wool traits in CSIRO's fine wool flock. Proc. Aust. Assn. Anim. Breed. Genet. 11:516-520. Available from: http://www.aaabg.org/proceedings/1995/ab95103.pdf (Accessed 05 May 2021.)

USDA-AMS. 2021. National wool review. Available from: https://usda.library.cornell.edu/concern/publications/wh246s153?locale=en&page=3#release-items (Accessed 9 October 2021.)

USDA-ERS. 2020. U.S. supply and use estimates and prices. Available from: https://www.ers.usda.gov/webdocs/DataFiles/48516/U.S.WoolSupplyandDemand.xlsx?v=5600.8 (Accessed 14 March 2021.)

USDA-NASS. 2005. Sheep and Goats. Washington, D.C. 1-05. Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/000000018/8623j1432/3j333499x/SheeGoat-01-28-2005.pdf. (Accessed 15 February 2022).

USDA-NASS. 2022. Sheep and Goats. Fort Collins, CO. N1949.1611. Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/000000018/pv63h240d/9880wt403/shep0122.pdf. (Accessed 15 February 2022).

Vandepitte, W.M. and L. N. Hazel. 1977. The effect of errors in economic weights on the accuracy of selection indexes. Ann. Genet. Sel. Anim. 9:87-103. doi: https://doi.org/10.1186/1297-9686-9-1-87

Wilton, J. W., D. Anthony Evans, and L. D. Van Vleck. 1968. Selection indices for quadratic models of total merit. Biometrics. 24(4):937-949. doi: 129.130.19.169

Wood, E. 2003. Textile properties of wool and other fibres. Wool Tech. and Sheep Breed. 51(3):272-290. Available from: https://www.sheepjournal.net/index.php/WTSB/article/view/1711/1699 (Accessed 03 March 2021.)

Yamada, Y., K. Yokouchi, and A. Nishida. 1975. Selection index when genetic gains of individual traits are of primary concern. Japan. J. Genet. 50:33-41. doi: https://doi.org/10.1266/jjg.50.33

Table 3.1 Descriptive statistics of NSIP wool phenotypes for breeds A and B

Trait	Breed	Number of observations	Mean	Variance
Grease fleece weight, kg	A	11,872	3.70	0.65
	B	27,917	4.21	0.72
Fiber Diameter, micron	A	9,880	21.43	2.21
	B	18,035	21.82	1.78
Staple length, mm	A	11,277	81.21	203.63
	B	19,830	88.50	324.36
Fiber diameter coefficient of variation, percentage	A	8,803	18.41	3.77
	B	5,472	19.22	5.18
Curvature, degree	A	6,009	95.40	155.75
	B	2,661	103.40	167.70

Table 3.2. Economic values for index A, B, C, and D

Index	Trait	Economic value ($/trait unit)	Genetic Standard Deviation	Relative economic value ($/genetic SD)
Index A	Grease fleece weight, kg	6.08	0.35	2.125
	Fiber diameter, micron	-0.502	1.14	-0.575
	Staple length, mm	0	8.03	0
	Fiber diameter coefficient of variation, percentage	-0.039	1.41	-0.055
	Curvature, degree	0.0042	6.01	0.025
Index B	Grease fleece weight, kg	6.08	0.35	2.125
	Fiber diameter, micron	-0.276	1.14	-0.316
	Staple length, mm	0	8.03	0
	Fiber diameter coefficient of variation, percentage	-0.039	1.41	-0.055
	Curvature, degree	0.0042	6.01	0.025
Index C	Grease fleece weight, kg	5.75	0.35	2.009
	Fiber diameter, micron	-0.502	1.14	-0.575
	Staple length, mm	0	8.03	0
	Fiber diameter coefficient of variation, percentage	-0.039	1.41	-0.055
	Curvature, degree	0.0042	6.01	0.025
Index D	Grease fleece weight, kg	5.75	0.35	2.009
	Fiber diameter, micron	-0.276	1.14	-0.316
	Staple length, mm	0	8.03	0
	Fiber diameter coefficient of variation, percentage	-0.039	1.41	-0.055
	Curvature, degree	0.0042	6.01	0.025

Table 3.3. Descriptive statistics of NSIP EBV records within the top 10% of Western Range Index values (14,501 animals)

Trait	Mean	Maximum	Minimum	Standard Deviation
Grease fleece weight, kg	10.55	44.13	-14.13	7.51
Fiber Diameter, micron	-0.23	4.84	-2.97	0.70
Staple length, mm	2.59	25.21	-13.94	4.46
Fiber diameter coefficient of variation, percentage	0.27	4.23	-2.30	0.71
Curvature, degree	-0.86	16.73	-19.45	3.22

Table 3.4. Index coefficients for index A, B, C, and D

Index	Traits	Index coefficient
Index A	Grease fleece weight, kg	6.080
	Fiber diameter, micron	-0.502
	Staple length, mm	-0.088
	Fiber diameter coefficient of variation, percentage	-0.039
	Curvature, degree	0.0042
Index B	Grease fleece weight, kg	6.080
	Fiber diameter, micron	-0.276
	Staple length, mm	-0.097
	Fiber diameter coefficient of variation, percentage	-0.039
	Curvature, degree	0.0042
Index C	Grease fleece weight, kg	5.750
	Fiber diameter, micron	-0.502
	Staple length, mm	-0.082
	Fiber diameter coefficient of variation, percentage	-0.039
	Curvature, degree	0.0042
Index D	Grease fleece weight, kg	5.750
	Fiber diameter, micron	-0.276
	Staple length, mm	-0.091
	Fiber diameter coefficient of variation, percentage	-0.039
	Curvature, degree	0.0042

Table 3.5. Efficiency losses for index A, B, C, and D

Index	Trait	"True" economic value	Efficiency loss at +50%	Efficiency loss at -50%
Index A	Grease fleece weight, kg	6.08	0.0566	0.0051
	Fiber diameter, micron	-0.502	0.0136	0.0113
	Staple length, mm	0	0	0
	Fiber diameter coefficient of variation, percentage	-0.039	0.0001	0.0001
	Curvature, degree	0.0042	0.0000	0.0000
Index B	Grease fleece weight, kg	6.08	0.0139	0.0013
	Fiber diameter, micron	-0.276	0.0033	0.0029
	Staple length, mm	0	0	0
	Fiber diameter coefficient of variation, percentage	-0.039	0.0001	0.0001
	Curvature, degree	0.0042	0.0000	0.0000
Index C	Grease fleece weight, kg	5.75	0.0641	0.0058
	Fiber diameter, micron	-0.502	0.0155	0.0129
	Staple length, mm	0	0	0
	Fiber diameter coefficient of variation, percentage	-0.039	0.0001	0.0001
	Curvature, degree	0.0042	0.0000	0.0000
Index D	Grease fleece weight, kg	5.75	0.0159	0.0014
	Fiber diameter, micron	-0.276	0.0038	0.0033
	Staple length, mm	0	0	0
	Fiber diameter coefficient of variation, percentage	-0.039	0.0001	0.0001
	Curvature, degree	0.0042	0.0000	0.0000

Table 3.6. Spearman rank correlations between the Western Range Index and index A, B, C, and D

Index	Trait	"True" economic value	Correlation at +50%	Correlation at -50%
Index A	Grease fleece weight, kg	6.08	0.2805	0.2812
	Fiber diameter, micron	-0.502	0.2804	0.2810
	Staple length, mm	0	0.2807	0.2807
	Fiber diameter coefficient of variation, percentage	-0.039	0.2807	0.2807
	Curvature, degree	0.0042	0.2807	0.2807
Index B	Grease fleece weight, kg	6.08	0.2803	0.2808
	Fiber diameter, micron	-0.276	0.2802	0.2806
	Staple length, mm	0	0.2804	0.2804
	Fiber diameter coefficient of variation, percentage	-0.039	0.2804	0.2804
	Curvature, degree	0.0042	0.2804	0.2804
Index C	Grease fleece weight, kg	5.75	0.2805	0.2813
	Fiber diameter, micron	-0.502	0.2804	0.2811
	Staple length, mm	0	0.2808	0.2808
	Fiber diameter coefficient of variation, percentage	-0.039	0.2807	0.2808
	Curvature, degree	0.0042	0.2808	0.2808
Index D	Grease fleece weight, kg	5.75	0.2803	0.2808
	Fiber diameter, micron	-0.276	0.2803	0.2806
	Staple length, mm	0	0.2804	0.2804
	Fiber diameter coefficient of variation, percentage	-0.039	0.2804	0.2804
	Curvature, degree	0.0042	0.2804	0.2804