ASAS CENTENNIAL PAPER: Impacts of animal science research on United States sheep production and predictions for the future[1]

C. J. Lupton[2]

Texas AgriLife Research, Texas A&M System, San Angelo 76901-9714

ABSTRACT: One hundred years ago, there were more than 48 million sheep in the United States. In 1910, they were valued at $4/head, with 43% of income coming from the sale of sheep, lambs, and meat and 57% coming from wool. Over the years, fluctuations in this ratio have challenged the breeder and researcher alike. By 2007, sheep numbers had declined to 6.2 million, with the average sheep shearing 3.4 kg of wool (representing <10% of income), 0.2 kg more than in 1909 but 0.5 kg less than fleeces in 1955. Sheep operations have declined by more than 170,000 in the past 40 yr. A cursory examination of this information might lead one to conclude that animal science research has made little impact on sheep production in the United States. On the contrary, lamb crops in the new millennium (range = 109 to 115%) are greater than those recorded in the 1920s (85 to 89%) and dressed lamb weights increased from 18 to 32 kg from 1940 to the present. In the past century, researchers conducted thousands of investigations, with progress reported in new, existing, and crossbreed evaluations, quantitative and molecular genetics, selection, nutrition, fiber, meat, hides, milk, growth, physiology, reproduction, endocrinology, management, behavior, the environment, disease, pharmacology, toxicology, and range, pasture, and forage utilization such that a vast amount of new information was accrued. Our understanding of sheep has benefited also from research conducted on other species, and vice versa. Many factors that have contributed to the decline in the sheep industry are not influenced easily by academic research (e.g., low per capita consumption of lamb meat, predation, reluctance to adopt new technologies, cost and availability of laborers with sheep-related skills, and fewer young people pursuing careers in agriculture). The size of the US sheep industry is expected to remain stable, with possible slow growth in the foreseeable future. To remain profitable, producers will take advantage of new (or previously unused) technologies, the desire of the public for things natural, domestic niche and international fiber markets, and the ability of the sheep to control noxious weeds and thrive in suboptimal ecosystems.

Key words: future, impact, research, sheep production

©2008 American Society of Animal Science. All rights reserved.

J. Anim. Sci. 2008. 86:3252–3274
doi:10.2527/jas.2008-1148

INTRODUCTION

"If a tree falls in the forest and no one is around to hear it, does it make a sound?" This age-old philosophical riddle may have a parallel in sheep research and production. "If a sheep research project is conducted and no producers hear (or read about) it, does it have an impact on the industry?" Of course, the answer depends on whom you ask. If you asked a group of uninformed lamb-eating or wool-wearing consumers, they might respond by saying they were not aware of any impacts that research had ever made on sheep production. If, on the other hand, you asked a group of informed breeders, producers, or sheep researchers, they would all likely be able to produce a short list of research topics that have made a significant impact on the industry. In fact, all research that has ever been conducted (and reported) has made a measurable impact on today's sheep industry, although it may be infinitesimal in some cases. My task in preparing this manuscript was to delve into 100 yr of animal (but primarily sheep-related) research literature and decide (with the assistance of 21 colleagues) which research has made an impact. Therefore, this is our collective opinion, with apologies to the thousands of animal scientists whose research will not be mentioned. It is unfortunate that so much technology produced by sheep researchers was or may never be used by the industry because of the constraints of earlier and current production systems.

[1]I am grateful to my colleagues for sharing their sheep-related knowledge with me and to B. S. Engdahl for her valuable assistance with the references and proofreading.

[2]Corresponding author: c-lupton@tamu.edu

Received May 1, 2008.
Accepted June 27, 2008.

This report examines the impacts of animal science research on US sheep production during the past 100 yr. Because it was prepared for the centennial celebration of the American Society of Animal Science (formerly the American Society of Animal Production), scientists who conducted their research in this country and reported their results in the *Journal of Animal Science* have received primary attention. However, it is recognized that research resulting in major impacts on sheep production has been conducted and reported elsewhere, and an effort was made not to overlook the major contributions.

MATERIALS AND METHODS

Data were obtained and summarized to provide a short overview of some of the major numerical changes that occurred in the sheep industry during the previous 100 yr. All sheep- and wool-related statistics were obtained or calculated from Quick Stats, an agricultural statistics database maintained by the National Agricultural Statistics Service, USDA.

Initially, 39 research and extension scientists who are current (n = 33) or past (n = 6) members of 2 national coordinating committees (Western Extension, Research, and Academic Coordinating Committee 039, "Coordination of sheep and goat research and education programs for the western states" and North Central Extension, Research, and Academic Coordinating Committee 190, "Increased efficiency of sheep production") and 4 professionals that work for sheep associations in marketing and promotion (n = 3) and a national feed company (n = 1) were contacted and independently asked to list research topics in their field of expertise that they considered had made a major impact on sheep production in the United States. Their responses (n = 21, 49% response rate) were combined and form the basis for most of the topics covered in this report. Subsequently, literature searches were conducted primarily, but not exclusively, in the *Journal of Animal Science* database, and an attempt was made to recognize the work of those scientists that initiated or made a highly significant contribution to specific research areas. Needless to say, all contributions were not recognized. My only excuses are the shortage of time in which to conduct and space in which to report a more thorough review. I hereby apologize for all oversights and assure any affected scientists that none was intentional.

RESULTS AND DISCUSSION

Sheep Industry Trends

The sheep population of the United States has fluctuated considerably during the past 100 yr. Between 1908 and 1923, sheep numbers declined from 48.2 to 36.8 million before increasing to 56.2 million by 1942. Since then, sheep numbers have declined to 6.2 million at present. From 1921 to the present, live and dressed weights at slaughter have increased steadily from 36.3 and 17.2 kg to 62.6 and 31.8 kg, respectively, and lamb crops have increased from 87% in 1924 to 110% in 2007. Wool production declined commensurate with the number of sheep shorn, with the greatest production, 176 million kg, occurring in 1942 and the least amount, 15.7 million kg, being shorn in 2007. Wool prices in the United States tended to follow international trends, with US wools invariably lower priced than wools of comparable grade from Australia, the leading exporter of high-quality wools. The recent low greasy price of $0.73/kg occurred in 2000, whereas the most recent high, $3.04/kg, was received in 1988. The previous low price for wool, $0.43/kg, occurred in 1971 (prices not adjusted for inflation). Since 1965, the number of operations with sheep had declined from 241,290 to 70,590 by 2007, with a current average flock size of 88 sheep per operation.

Searching the Journal

A search of the *Journal of Animal Science* database from January 1910 to April 2008 using the following search criteria resulted in 3,917 titles being listed: the key words sheep, wool, lamb, ewe, ram, ovine, fleece (with any of these words in the title or abstract). The majority of articles reported research with sheep. However, a few were not bona fide sheep manuscripts but were concerned with topics such as rabbit and qiviut wool or the like. This online search capability of the *Journal* is a tremendous resource.

Genetics

This section comprises animal breeding, including breed development, breed and crossbreed evaluations (with particular emphasis on use of the Finnsheep to increase lamb production), improvement of existing breeds through selection, and quantitative genetics to estimate genetic parameters and predict genetic merit of individual animals within a breed, all fields that have greatly influenced sheep production in the United States. A recent addition to the field of study is analysis of QTL, this being a region in the genome that affects a specific trait or number of traits. The QTL approaches require accurate phenotypic, pedigree, and genotypic data from a large number of individuals.

Quantitative and Population Genetics

The foundation of animal breeding research was undoubtedly the work of Mendel (1865). Principles of population genetics developed by Wright (1921) using guinea pigs were extended by Lush and his students, who provided leadership in the application of quantitative statistics and genetic information to the breeding of farm animals. Lush (1937) authored a book that became a classic, *Animal Breeding Plans*, which greatly influenced animal breeding around the world. His work was later extended to sheep by Hazel (1943), Terrill and Hazel (1943), Hazel and Terrill (1945, 1946), Shelton et al. (1954), and numerous others who espoused the concepts and methods of Lush and used them to develop breeding objectives and effective genetic improvement programs (including the construction of selection indexes) that required estimates of phenotypic variation, heritability, repeatability, genetic and phenotypic correlations, and values for the economically important traits. Fogarty (1995) reviewed the genetic and phenotypic parameters for measures of growth, wool production, and reproduction in sheep, likely the most thorough review of this topic ever conducted (173 references, including many from US researchers), which included breeds common in the United States. That report has since been updated (Safari and Fogarty, 2003). This information contributed to the genetic evaluation of potential breeding stock and the establishment of improvement programs in the United States and many sheep-producing countries around the world. Sheep Genetics Australia currently maintains the world's largest sheep genetics database and uses it to calculate "credible and accurate" breeding values that support terminal, dual-purpose, and maternal breeders (LAMBPLAN; Banks, 1990) and Merino breeders (MERINOSELECT). In the United States, the National Sheep Improvement Program (**NSIP**), supported by breeders and the American Sheep Industry Association, was implemented in 1987 (Wilson and Morrical, 1991). Originally designed to provide within-flock genetic evaluations, the program evolved to issuing across-flock, multiple-trait genetic evaluations for the Targhee, Suffolk, and Polypay breeds (Notter, 1998). In 2007, NSIP provided EPD information on multiple traits for the following enrolled breeds, representing 129 flocks: Targhee, Polypay, Dorset, Hampshire, Suffolk, Katahdin, Columbia, Romney, Dorper, Coopworth, and Rambouillet (D. R. Notter, Virginia Polytechnic Institute and State University, Blacksburg; personal communication). Although this science-based program is considered by most academics to be the best method currently available for making genetic evaluations of specific traits, numerous reasons have been suggested for the low adoption rate of this technology. Some breeders claim they have neither the time nor the budget to make or submit the required objective measurements. Therefore, although the NSIP has already had a positive impact on sheep production in the United States, especially in the Targhee breed, its potential impact has yet to be realized. On the other hand, central and on-the-farm ram performance tests were conducted in numerous states for many years [14 and 23, respectively, in 1980 according to G. A. Allen Jr. (as cited in Parker and Pope, 1983)]. Central tests, although now relatively few in number, have been credited by the industry for continuously improving some economically important traits while maintaining others (Trinidad, 2007). For example, the program in Texas was initiated in 1948. Shelton et al. (1954) reported progress after 4 yr and on the genetic changes that had occurred after 28 yr (Shelton, 1979). Since its inception, the Rambouillet (predominant breed) rams completing this test have increased in BW, ADG, clean fleece weight, and staple length from 85 to 112 kg, 0.17 to 0.39 kg/d, 3.0 to 5.1 kg, and 8.5 to 12.0 cm, respectively, while maintaining the average fiber diameter of wool at 22 μm (Waldron and Lupton, 2008). Concurrently, marked reductions have occurred in the amount of wool in the face and wrinkles on the body. After 60 yr, progress in recent times is considerably slower than it was in earlier years. However, improvement in wool production should still be possible without undermining any of the size, gain, lamb production, or meat quality traits of this breed. Feed efficiency is another trait in which progress should be possible through selection. The West Virginia Ram Performance Test uses cutting-edge technology to evaluate residual feed intake as a measure of feed efficiency and to include these measures as an important part of the selection index (Smith, 2006). In the 2006 test, residual feed intake ranged from 57 to −33 kg for the 63-d test, indicating that the most efficient ram ate 33 kg less feed than expected and that the least efficient ram ate 57 kg more than expected. With this amount of variation in a moderately heritable trait, the potential for improvement in feed efficiency is high.

Sheep Breeding

Terrill (1958) described progress in sheep breeding during the first 50 yr of the American Society of Animal Science. He pointed out "that sheep breeders of the past 50 yr have continued to improve on practices which began possibly 7,000 to 8,000 years ago." Without the assistance of a computerized browser, Terrill assembled 336 pertinent references in support of the information he presented, a stellar achievement that has left us with a valuable resource concerning sheep breeding during the first 50 yr of our society. For that period, Terrill reported improvements in fleece weights (from 3.2 to 3.9 kg, a trend that reversed in the subsequent 50 yr) and in lambs saved and slaughter weights. The development of new breeds was credited for some of this improvement. Terrill also expounded at length on the advantages of crossbreeding, primarily for market lamb production, and again referenced many studies in which various breeds of sires and dams were used. By 1958, much information on the inheritance of traits had been generated. Despite the sometimes wide ranges that have been reported, heritability estimates of traits were generally assigned to 1 of 3 categories: high (face covering, skin folds, staple length, fiber diameter, and birth coat), medium (BW at birth, weaning, and yearling; ADG; clean and greasy fleece weights; clean yield; wool-processing traits; index of overall merit; color on legs; milk production; lambing date; resistance

Table 1. Number of articles published in the *Journal of Animal Science* between 1910 and 2008 by sheep breed

Breed	Number	Year first mentioned	Last year mentioned
Barbados	17	1979	2004
Booroola Merino	11	1986	2008
Cheviot	28	1928	1999
Columbia	150	1931	2005
Coopworth	9	1988	2008
Corriedale	40	1934	2008
Debouillet	4	1990	1999
Dorper	5	2000	2007
Dorset	150	1928	2008
East Friesian	3	2000	2005
Finnsheep	88	1972	2008
Hampshire	69	1931	2007
Karakul	12	1934	1977
Katahdin	3	1997	2007
Leicester	25	1925	2008
Lincoln	7	1930	1965
Merino	68	1925	2008
Montadale	6	1993	2005
Navajo-Churro	18	1939	2004
Polypay	43	1984	2005
Rambouillet	274	1927	2007
Romanov	30	1986	2007
Romney	26	1931	1995
Scottish Blackface	5	2006	2007
Southdown	51	1925	1991
Saint Croix	18	1981	2004
Suffolk	264	1934	2008
Targhee	154	1939	2008
Texel	25	1958	2007

to parasites; number of nipples; dietary selection of certain plant species), and low [type of birth (single or multiple), conformation, and condition score].

So what of the next 50 years? The data in Table 1 give an indication of the extent to which US animal scientists (primarily) have studied various breeds of sheep during the last century. Because many of the studies were multibreed comparisons (e.g., Ercanbrack and Knight, 1998; Freetly and Leymaster, 2004) and evaluations of crossbred sheep (e.g., Freking et al., 2000; Afolayan et al., 2008), multiple breeds and crosses were the subjects of numerous studies. Therefore, caution is necessary in attempting to correlate the number of articles (research output) written about a particular type of sheep with its impact on the sheep industry.

An outstanding contribution of research to the sheep industry was undoubtedly the development of new breeds. The Columbia breed was started by the USDA in 1912 with crosses of Lincoln rams on Rambouillet ewes (Marshall, 1949). This breed was designed to replace the many ad hoc crosses that producers were making on the range by using long-wool sire breeds and Rambouillet ewes to produce larger market lambs. Although developed primarily for the western range states, this breed is now present in most states. Mature ewes weigh from 68 to 102 kg and shear 4.5 to 7.3 kg of grease wool (45 to 55% clean yield) in the range of 24 to 31 μm. Breeding that resulted in the Panama was initiated about the same time by a private group that used Rambouillet rams on Lincoln ewes. The Romeldale, developed in California, was initiated by crossing Romney rams with Rambouillet ewes. Terrill (1958) stated that these 3 breeds were representative of large numbers of range and commercial sheep in the United States at the time of his writing. In 1928, the USDA began to develop (and ultimately released) the Targhee breed (Terrill, 1947), a "comeback" type of sheep produced by crossing Rambouillet rams with Lincoln-Rambouillet, Corriedale-Lincoln-Rambouillet, Corriedale, and Columbia ewes (i.e., basically, a three-quarters fine-wool sheep). Mature ewes of this breed are generally smaller (56 to 90 kg) than Columbia ewes and produce finer wool (21 to 25 μm). The premier sale for Targhee rams is the Montana Ram Sale, which originally catered to breeders in Montana, South Dakota, and Wyoming. Today, Targhee sheep are present in more than 38 states.

The next breed developed by the USDA was the Polypay (Hulet et al., 1984; Snowder, 2001), which had a reproductive capacity markedly superior to that of traditional fine-wool western range sheep. This effort to develop a new breed was preceded by numerous studies conducted in the 1970s in which crosses with the prolific Finnsheep (e.g., Dickerson et al., 1975; Boylan et al., 1976) and other prolific breeds, such as the Booroola Merino (Willingham et al., 1988), were evaluated. The original intent was to develop a range-adapted breed with high lifetime prolificacy that would breed consistently as a yearling, lamb more than once in a year, and produce lambs with a desirable growth rate and carcass quality. The Polypay is a 4-breed composite of Targhee (large body size, long breeding season, fine wool), Rambouillet (adaptability, hardiness, productivity, fine wool), Dorset (superior milking ability, carcass quality, early puberty, and long breeding season), and Finnsheep (high prolificacy, early puberty, short gestation). The Polypay is considered to be a medium-sized sheep (mature ewes weigh 60 to 82 kg) that produces 2.7 to 4.5 kg of grease wool (55 to 60% clean yield) annually, having wool in the 24- to 33-μm range. Sheep that were very similar to the USDA Polypays were also developed by independent breeders (e.g., G. Nicholas in California) and later accepted as Polypays. The breed is now present in many farm flocks as well as western range states throughout the United States and in Canada. As with any other highly productive sheep, increased productivity of the Polypay ewe is dependent on the ewe's nutritional requirement being met throughout the production year.

The Montadale breed was developed from Columbia × Cheviot crosses in the 1940s by E. H. Mattingley, a Midwestern commercial lamb buyer. The breed, found mainly in farm flocks today, is medium in size, with ewes ranging from 70 to 80 kg and rams from 90 to 125 kg. Montadale sheep are considered to be dual-purpose, with ewes reported to grow 3 to 5 kg of exceptionally white wool annually having an average fiber diameter in the range of 25 to 30 μm and yielding 50 to 60%.

The Katahdin breed was initiated in Maine in the late 1950s by M. Piel. Starting with imported Caribbean hairsheep, crosses of many breed combinations (Tunis, Southdown, Hampshire, Suffolk and other down breeds, Cheviots, Wiltshire Horn, and St. Croix) were used to arrive at today's medium-sized, polled, prolific, parasite-resistant (Vanimisetti et al., 2004), heat-tolerant, shedding, white and colored hairsheep. The latest breed to be developed in the United States was the Royal White by W. Hoag, who selected from Dorper × St. Croix crosses to produce a medium-sized, low-maintenance hairsheep. A description of hairsheep breeds (Barbados Blackbelly, St. Croix, Katahdin, and Dorper) that were considered to have immediate relevance to US sheep production was written by Wildeus (1997). An influential book on hairsheep of Western Africa and the Americas was edited by Fitzhugh and Bradford (1983).

Multiple-breeder cooperation to accelerate genetic change has been advocated by numerous US sheep geneticists. Such group-breeding schemes have been successful in Australia, New Zealand, and other countries. Perhaps the independent nature of some US breeders has limited their use in this country. One program, Texas Rambouillet Superior Genetics Association, involving 10 breeders who use traditional methods as well as NSIP EPD to select the next generation, is currently in its 10th year and appears to be achieving its goals, which are commensurate with the great amount of effort that is expended (Campbell, 2008).

Breed and Crossbreed Evaluations

Numerous studies have been conducted in which pure breeds of sheep were evaluated and compared in specific production systems (e.g., Ercanbrack and Knight, 1998; Leymaster, 2002). The many breed and crossbreed evaluations and comparisons that have been reported have affected the sheep industry today by determining appropriate roles (e.g., maternal, paternal, or general purpose) for different sheep breeds and crossbreeds and have influenced breeders directly or indirectly (via prices paid by feeders, packers, or wool buyers, or the fitness of the breed for a particular production system, for example) to embrace specific breeds or crossbreeds. Development of the aforementioned breeds was followed by numerous comparative studies in which researchers were able to document specific advantages and shortcomings of the new breeds and their crosses compared with existing breeds and their crosses in specific environments. For example, Sidwell and Miller (1971a,b,c) and Sidwell et al. (1971) compared the productivity (lamb and wool) of purebred Hampshire, Targhee, Suffolk, Dorset, and crossbred Columbia × Southdown × Corriedale ewes and all their crosses in a major study conducted in the 1960s. When ewes were evaluated for lamb and wool production per unit of BW, the Columbia × Southdown × Corriedale ewes had the greatest index, followed by Targhees and Suffolks (Sidwell and Miller, 1971c). Research with Finnsheep began in 1968, producing a major and lasting impact on the industry, with Finnsheep crossbred ewes providing more lambs when management was adequate (Dickerson, 1977). More recently, 5 sire breeds (Dorset, Finnsheep, Romanov, Texel, and Montadale) and 2 dam breeds (Composite III and Northwestern Whiteface) were evaluated by producing and evaluating 2 crossbred populations. Effects of the ram breeds (Freking et al., 2000); reproduction of F_1 ewes in the fall (Casas et al., 2004) and spring (Casas et al., 2005) mating seasons; wool characteristics of F_1 ewes (Lupton et al., 2004); and survival, growth, and carcass traits of F_1 lambs (Freking and Leymaster, 2004) were reported. It was concluded that commercial lamb production could be improved markedly by greater use of Romanov-crossbred ewes in maternal roles of terminal crossbreeding systems. Comprehensive evaluation of breeds provides critical information to producers concerning the appropriate use of breeds in crossbreeding systems to meet specific production environments and marketing goals (Casas et al., 2005).

The Dorper currently is receiving increased attention from researchers and producers alike. It appears to have potential as an "easy-care" breed that does not require shearing and is superior in conformation and muscling relative to other hairsheep breeds. Snowder and Duckett (2003) evaluated the Dorper as a terminal sire breed and concluded that Dorper × Columbia crossbred lambs were similar to Suffolk × Columbia and Columbia lambs in terms of 118-d weaning weight, postweaning ADG, feed efficiency, and carcass characteristics. Notter et al. (2004) reported that Dorper-sired lambs were similar in growth rate, lamb survival, and carcass merit to lambs sired by Dorset rams. Dams were 50% Dorset × 25% Rambouillet × 25% Finnsheep in that study. However, compared with Caribbean hair breeds and the derivative Katahdin, Dorpers exhibited little resistance to *Haemonchus contortus* (Vanimisetti et al., 2004). Other researchers (e.g., D. F. Waldron, Texas AgriLife Research, San Angelo; personal communication) are evaluating the Dorper as a maternal breed in extensive production systems, the purpose for which the breed was developed in South Africa.

Most crossbreeding evaluations conducted in the past 30 yr have been concerned primarily with increasing lamb production by increasing the number of lambs born per ewe. In fact, "breeding for improvement of meat production in sheep" was the subject of a special edition of the *Sheep and Goat Research Journal* (2002, vol. 17, no. 3). Because many production areas and systems cannot support more lambs without having considerably more inputs, several crossbreeding evaluations were designed with the purpose of increasing wool production and value (e.g., Snowder et al., 1997).

To date, these have had a minimal impact on the US sheep industry. In contrast, studies involving the East Friesian (e.g., Thomas et al., 2001) and other foreign and domestic breeds (Sakul and Boylan, 1992) for commercial milk production have spawned interest, particularly among producers in the Upper Midwest and New England. Specialty cheese production from sheep milk appears destined to become an economically important domestic agricultural industry in the near future (Thomas, 2004).

Molecular Genetics

This field of study has probably had the least impact on sheep production to date but promises to have the greatest impact in the future. One objective of scientists working with the sheep genome is to determine the exact order of nucleotides or base pairs in genes and chromosomes that constitute DNA molecules isolated from sheep. Because DNA from individual organisms is unique, it was recognized more than a decade ago that genetic marker technologies such as marker-assisted selection, parentage identification, and gene introgression could be applied to livestock selection programs (e.g., Davis and DeNise, 1998). Wheeler (2003) discussed practical applications of transgenesis in livestock production, including enhanced prolificacy and reproductive performance, increased feed utilization and growth rate, improved carcass composition, improved milk production and composition, and increased resistance to disease. Perhaps the most publicly recognizable event involving sheep and molecular genetics was the successful cloning of Dolly (July 5, 1996 to February 14, 2003), the first animal to be cloned from an adult somatic cell (taken from a mammary gland) by using the process of nuclear transfer (Campbell et al., 1996). A major milestone in sheep genomics occurred in November 2006 when the International Sheep Genomics Consortium, a partnership of scientists with funding from the United States, Australia, the United Kingdom, New Zealand, France, and Kenya, released a virtual map of the sheep genome by using information from the cow, dog, and human genome. Having this resource is expected to improve the efficiency of sheep research into gene function as scientists attempt to find molecular methods to improve wool quality, carcass traits (e.g., Johnson et al., 2005), fertility, the ability to cope with parasites, and so on. Sheep genome maps and other genome resources are available at several locations on the World Wide Web, including a USDA-ARS Web site (http://www.marc.usda.gov/genome/sheep/sheep.html; accessed April 29, 2008) and the National Institutes of Health, National Center for Biotechnology Information (http://www.ncbi.nlm.nih.gov/genome/guide/sheep; accessed April 29, 2008). Application of genomic information in livestock was the subject of a recent review by Sellner et al. (2007). More specifically, application of genomics to sheep production was the subject of a recent symposium at the Annual Meeting of the American Society of Animal Science (Beever and Markey, 2006; Bidwell and Cockett, 2006; Cockett et al., 2006; Fischer, 2006; Wilson, 2006). Of all the molecular genetic work that has come to fruition to date, the major achievements, from the United States (and the world) sheep industry's point of view, are probably the DNA tests for spider lamb syndrome carriers (Cockett et al., 1999; Cockett and Beever, 2001) and for scrapie susceptibility (Baylis and Goldmann, 2004). Other important work is leading to an understanding of the Booroola gene (*FecB*; Wilson et al., 2001; McNatty et al., 2007), which was the first major gene for prolificacy identified in sheep; the Callipyge gene (Freking et al., 1998); and the Woodlands mutation (*FecX2*^{W}; Feary et al., 2007). Registered breeders no doubt appreciate having access to genetic tools that permit them to establish the parentage of lambs in multisire matings, as reported by Laughlin et al. (2003). Many other potentially important studies are in progress.

Reproduction

Reproductive efficiency, defined as the BW of the lamb weaned or marketed per ewe exposed, is the major factor affecting profitability of most commercial sheep operations. It is therefore not surprising that tremendous research effort has been expended on increasing or optimizing (for the resource) reproductive efficiency. Attempts to improve reproductive efficiency have been concerned with increasing the ovulation rate and reducing embryo wastage and lamb losses. A shortcut to achieving one or more of these goals was to switch to a more prolific breed or develop a crossbreeding program to increase genetic potential for increased ovulation rate. Use of the Finnsheep and Romanov for this purpose is discussed in the Genetics section.

Artificial insemination of farm animals has had an enormous impact worldwide in some species (e.g., dairy cattle), but less so in sheep (Foote, 2002). Nevertheless, vaginal and cervical insemination of ewes has been used to produce millions of lambs in other countries and is consistently successful with fresh, diluted semen. However, after a successful method of freezing ram semen was developed (Salamon, 1967), results with these 2 methods using frozen semen proved much less reliable. Consequently, researchers turned to and developed a laparoscopic method of inseminating ewes that generally has a much greater success rate. Although many US sheep breeders do not use the laparoscopic inseminating technique routinely, it has had a major impact in research, and the technology has permitted rapid dissemination of foreign breeds (e.g., Finnsheep, Merino, East Friesian, Dorper) throughout North America. The acceptance of AI worldwide provided the impetus for developing related technologies such as cryopreservation and sexing of sperm, estrous cycle regulation, and embryo harvesting, freezing, culture and transfer, and cloning (Foote, 2002).

Detection of pregnancy in sheep by using ultrasound was first reported by Lindahl (1966). The technology has improved considerably over the years such that a competent technician with a battery-powered instrument can work through 200 ewes in a drenching ally in less than 2 h. Differentiating between open ewes and ewes carrying single or multiple lambs allows the producer to apply differential nutritional management. This technology continues to have a moderate impact on the US sheep industry, particularly with pure breeders and producers with prolific sheep.

Research has indicated that most sheep breeds should be selected, managed, and bred to give birth as yearlings because this has such a dramatic effect on the lifetime productivity of the ewe. Another advantage is shorter generation intervals, and therefore more rapid genetic gain. However, these gains come with potential risks in terms of birthing difficulties and slower growth rates of young dams. This practice is relatively common in US farm flocks but is used much less in extensive range operations, in which the lambs are typically weaned at a later age.

Prenatal losses, most of which occur within the first 18 d of pregnancy (e.g., Hulet et al., 1956), account for approximately 30% of all fertilized eggs. Although the reasons for this are not always obvious, the viability of the fertilized egg is known to be breed dependent (Meyer, 1985) and is particularly sensitive to poor nutrition, overfeeding, toxins, high temperatures, other stressors, and certain diseases, especially in the first 3 wk of pregnancy. Dead embryos and fetuses are reabsorbed, aborted, or mummified in the womb. Broad-spectrum therapies for undiagnosed prenatal losses are generally unsuccessful. Dixon et al. (2007) recently characterized the timing of late-embryonic and fetal losses and concluded that (as with cattle) reproductive wastage in the ewe could be reduced with greater concentrations of progesterone in the maternal serum. Finding a practical way to achieve this is a challenge for future research.

Most perinatal losses occur within 3 d after parturition. In the United States, this was estimated at 12% of all live births (Inskeep, 2002). Some of the factors contributing to the losses included ringwomb, malpresentations, malformations of the lamb, birth injuries, infections, starvation, and cold exposure. Losses were reported before and after the implementation of improved management practices [consisting primarily of placing lambs and their dam in 1.8 × 1.8 m plywood pens (jugs) for 3 d after birth], and a reduction from 12.6 to 4.1% was reported in lamb mortality of live lambs born. Birth and breed type and age of the dam also were shown to affect lamb mortality, even when jugs were used (Inskeep, 2002). Producers with more intensive operations are no doubt still using ewe and lamb confinement to help with this and other problems. However, although some large range operators used the technology in the past, the trend now is for easy-care, low-labor operations with considerably less input.

Breeding soundness of the ram for optimal performance is obviously an important aspect of reproductive success. Although there are numerous aspects to a thorough breeding-soundness examination (e.g., physical examination, BCS, genitalia examination, and semen evaluation), research has demonstrated that rams should also be tested for contagious epididymitis caused by *Brucella ovis* because it is the leading source of ram fertility problems in the United States. Because only approximately 50% of infected rams respond positively to antibiotics, the prescription for infected rams is to cull them from the flock. C.V. Kimberling of Colorado State University has been a long-term crusader in this field. Not only is breeding capacity a function of adequate sperm numbers of excellent quality, but it also depends on libido and serving capacity. Mating behavior can be tested and observed either in the field or in the pen. Marking systems can also be used to measure the activity of multiple rams. Low-performing rams are identified and eliminated from the breeding program. Reasons for variation in ram performance have been identified and can be categorized generally as genetic, social, biological, and management related. Researchers at the USDA-ARS US Sheep Experiment Station at Dubois, Idaho, have made major contributions to understanding the causes of variability in ram mating behavior (e.g., Terrill, 1937; Stellflug et al., 2006). The take-home message to producers has been to use serving capacity tests to select high-performance rams and reduce the number of rams with marginal sexual performance.

Using the proximity of a ram to terminate anestrus in breeding ewes is a reproductive management tool that has been explained (e.g., Watson and Radford, 1960) and reviewed (Martin et al., 1986) by researchers and used for years by sheep producers. Typically, ewes that have been away from rams for more than a month will ovulate 40 to 60 h after reintroduction of a ram. However, estrus does not occur with this ovulation. Estrus synchronized with ovulation will typically occur 19 to 23 d later. Breed of ewe influences the so-called "ram effect." Breeds that are known to have long anestrus periods may be totally unresponsive to rams during early anestrus, only becoming responsive closer to the end. In contrast, some fine-wool breeds (e.g., the Merino) that have shorter anestrus periods respond to the ram throughout anestrus (Inskeep, 2002). This is a very powerful tool that is used routinely by breeders to synchronize ewes and enhance out-of-season breeding.

Sheep are seasonal breeders, with the ewe exhibiting the most reproductive activity in the fall. Annual fluctuations in timing and duration of the nocturnal elevation in circulating melatonin is known to be a key factor influencing seasonal reproduction in sheep (Malpaux et al., 1996). Estrus synchronization allows for planning of parturition for times that may be more convenient or profitable. Methods of synchronization range from the relatively simple ram effect or alteration of light patterns, to methods as complex as varying timed hormonal treatments combined with light alteration and the ram effect. Hormones that have been used include melatonin, progestins, gonadotropins or GnRH, estrogens, and prostaglandin alone or in combination. Although effective hormone treatments for ewes have been established for synchronization and out-of-season breeding, none is currently approved for commercial use in the United States. With current public opinion being very much against hormonal treatment of food animals, the likelihood of increased use of hormones in the US sheep industry appears to be very low.

A dichotomy exists for sheep researchers and producers in the United States at this time in that one group is continuing to develop and use more intensive systems for accelerated lambing (e.g., the STAR system; Hogue, 1987), whereas the remainder are developing or searching for easy-care systems (Thonney et al., 2008) with minimum input (hence one reason for the increasing popularity of hairsheep; Notter, 2000). It will be interesting to see how much of the reproductive technology already developed will be used by producers in the event that regulations are altered to permit increased use.

Health

Although most may not have been discovered or developed by animal scientists, pharmaceuticals that have been brought to the market in the past 100 yr have provided researchers, producers, and consumers with healthier animals. In numerous cases, animal science research has complemented the medical or veterinary work by establishing the effects of particular drugs on production parameters. A short list of products that have influenced the sheep industry and are still used routinely in many parts of the country includes vaccines for anthrax, bluetongue, campylobacteriosis, caseous lymphadenitis, enterotoxemia and other clostridial diseases (including tetanus), enzootic abortion, footrot, leptospirosis and ram epididymitis; amprolium, lasalocid, and monensin for control of coccidia; numerous antimicrobial agents; and 3 families [benzimidazoles (white drenches), levamisoles (clear drenches), and avermectins] of products for control of stomach worms, including albendazole, cydectin, doramectin, fenbendazole, ivermectin, and levamisole. Misuse and overuse of these products has led to multiple-anthelmintic resistance in *H. contortus* worms in various parts of the country. Anthelmintic-resistant stomach worms now pose an enormous problem for sheep (and goat) producers worldwide (McKellar, 2006). Some practical recommendations for the rational use of anthelmintics (e.g., avoid introducing resistant worms; use an isolation pen for new stock, followed by posttreatment egg counting; and never underdose) have been communicated to the industry in an attempt to contain the problem. Recently, a method (the FAMACHA system) for detecting clinical anemia (indicative of worm infestation) using eye color scores in individual animals has been validated (Kaplan et al., 2004). By deworming only infested animals requiring treatment, producers save money, and the development of further resistance in nematodes is avoided. Numerous studies now indicate that providing supplemental protein to sheep with subclinical infections of gastrointestinal parasites improves their resilience and resistance to parasites (e.g., Coop and Kyriazakis, 1999). On the other hand, food restriction at or around the anthelmintic treatment has been shown to dramatically improve the efficacy of the avermectins (Ali and Hennessy, 1996). A discovery program for new families of anthelmintics for sheep and goats is unlikely because of the perceived poor rate of return to the animal health pharmaceutical industry. Selection programs for sheep with increased resistance to internal parasites have been and are being conducted because there is a proven genetic component to resistance, and possibly also tolerance. Estimated breeding values for parasite resistance are now being provided to breeders by using the Australian sheep genetic databases and to breeders of Katahdin sheep that use NSIP in the United States. In addition, genomic investigations are underway (e.g., Sheep CRC in Armidale, Australia, and others) with the objective of providing a DNA test that would identify resistant and resilient sheep. Other researchers are investigating the potential of natural products such as tannins (Min and Hart, 2003) and juniper products (T. Whitney, Texas AgriLife Research, San Angelo; personal communication). Part of the rationale for this approach is that the natural products, if found to be effective, could easily be introduced onto the market, whereas a new family of synthetic anthelmintics could take years to approve. There are, in fact, many highly effective drugs that are not authorized for sheep but that would contribute to improved welfare and more efficient productivity. The challenge is to find ways to exploit these therapeutics without endangering consumers and within the economic constraints placed on the pharmaceutical manufacturers (McKellar, 2006). Many other health issues exist for sheep maintained on pasture and in fields and pens, and animal scientists have been involved in studies of most of them.

Successful efforts to eliminate the screwworm in the southern states were initiated in Florida in 1958 (USDA, Agricultural Research Service, 1962) and have contributed more to increasing domestic animal production in this area of the country than any other program. The United States has been essentially free of the screwworm since 1966. The absence of screwworms is estimated to be worth more than $800 million annually to the livestock industry. Another successful USDA program initiated in 1960 took 12 yr to eradicate sheep scab (*Psoroptic scabies*).

Scrapie is a fatal, degenerative, infectious disease that affects the central nervous system of sheep. It belongs to the family of transmissible spongiform encephalopathies. Scrapie was first described in 1732 in Great Britain and the first case was diagnosed in the United States in 1947 in sheep originating from Britain. The causative agent is thought to be contained in a prion, a proteinaceous infectious particle that is highly resistant to degradation. Eradication of scrapie has been a national priority for some time because of its negative effects on domestic and international markets and the estimated cost to sheep producers of $20 million annually. After several failed attempts to eradicate the disease, USDA-Animal and Plant Health Inspection Service is currently managing a mandatory, industry-wide program (the Scrapie Eradication Program) aimed at identifying infected sheep, tracing them to the flock of origin, and providing effective cleanup strategies at the sources. The job of identifying infected sheep has been made easier by the development of 2 live-animal tests (lymphoid tissue from the third eyelid (O'Rourke et al., 2000) or a rectal mucosa biopsy (USDA-Animal and Plant Health Inspection Service announcement, April 2, 2008) as well as a DNA test for genetic resistance to the disease that is correlated with variation in the haplotypes of the prion (*PRNP*) gene at codons 136, 154, and 171 (Baylis and Goldmann, 2004). This latter test allows breeders to make genetic selections for scrapie-resistant animals. The availability of this test already has had a significant impact on purebred ram sales, particularly in the states that have prohibited entry of scrapie-susceptible sheep. There is some optimism that scrapie can be eliminated through genetic selection. There has been concern that some important sheep phenotypes could be lost in the process. However, molecular genetic studies conducted to date (e.g., Isler et al., 2006) have found little evidence of antagonistic relationships between the resistant prion haplotype and economically important production traits.

Spider lamb syndrome (Thomas and Cobb, 1986) is a genetic disorder causing skeletal deformities in lambs. The genetic mutation responsible for spider lamb syndrome was identified (Cockett et al., 1999) and a commercial DNA screening test for carriers is available. The test has been used successfully in Suffolk, Hampshire, Southdown, Shropshire, and Oxford sheep, so the industry now has an opportunity to eliminate the disorder.

Sore mouth (orf, contagious ecthyma; Linklater and Smith, 1993) is a zoonotic viral disease of the skin caused by a parapox virus. It occurs worldwide in lambs, kids, and susceptible adults. Researchers with the Texas Agricultural Experiment Station in Sonora (Boughton and Hardy, 1934) developed a vaccine, and millions of doses have been manufactured almost continuously from 1932 until the present and have been sold from that location to the sheep industry.

Rectal prolapse has been a costly health issue, particularly for lamb feeders. Much anecdotal evidence indicated a relationship with the length of the docked tail. Thomas et al. (2003) conducted a multistate cooperative study in which lambs (n = 1227) were docked short (tail was removed as close to the body as possible), medium (tail was removed at a location midway between its attachment to the body and the attachment of the caudal folds to the tail), or long (tail was removed at the attachment of the caudal folds to the tail). Short-docked lambs had a greater incidence of rectal prolapse (7.8%) than did lambs with a medium (4.0%) or long dock (1.8%). Thus, the association between short docking and rectal prolapse in lambs being finished on high-concentrate diets was strongly indicated. This is valuable information that show-ring exhibitors have been slow to adopt. In contrast, lamb feeders have recognized the problem and are applying discounts to animals with excessively short tails.

Nutrition Research

In his 50-yr review of sheep nutrition research (conducted between 1908 and 1958), Pope (1958) began by discussing what was known about sheep nutrition before 1908, namely, that sheep require between "1.0 and 1.6 lb digestible CP per 1,000 lb BW per day" (an amount not dissimilar from the quantities recommended today). Both Wolff (1874) and Kellner (1908) published feeding standards for sheep that included digestible protein, carbohydrates, and fats. Virtually no information was available on mineral feeding or of sheep requirements (except for the recommendation to make salt available), and vitamins were of no concern. Sheep nutrition trials (n = 194) conducted in Great Britain between 1844 and 1905 were summarized by Ingle (1910). Some very practical investigations had been conducted, including the effects of creep feeding on lean muscle in the carcass and experiments to evaluate the effects of feeding numerous types of grains, by-products, silages, and tubers to sheep (sound familiar?).

The period from 1908 to 1933 was an era in which animal scientists attempted to establish energy and protein requirements of sheep through many feeding trials and extrapolation from cattle data. In fact, work conducted in this era formed the basis of the recommendation for the maintenance energy requirements of sheep published 24 yr later (NRC, 1957). One of the earliest studies of mineral requirements of sheep was reported by Fraps (1918). Later, Fraps and Cory published several detailed articles (e.g., Fraps and Cory, 1940) over a 30-yr period on diet selection for sheep and goats. They also analyzed and cataloged in detail the nutritional values of range and harvested forages and feeds, which have not been matched before or since. During the next 25 yr, many experiments were conducted to determine more accurately the protein, energy, mineral, and vitamin requirements of sheep in different stages of production. Harris and Mitchell (1941a,b), and later Johnson et al. (1942), and subsequently numerous others reported that growing lambs could use urea, and that this compound could safely be used to replace 25 to 33% of the protein equivalent in the ration. Another important study (Loosli et al., 1949) reported that 10 essential AA are synthesized in large amounts in the rumen of sheep fed urea as the only source of nitrogen. In the early 1950s, exacting work to determine the digestible protein requirements of mature and pregnant ewes (45 to 60 g/head per d) was reported (e.g., Klosterman et al., 1951; Slen and Whiting, 1955) that later served as the basis for the NRC (1957) recommendation.

Much progress also was made in mineral research during this period. Meyer and Weir (1954) reported on the use of high levels of salt to regulate protein supplementation of breeding ewes. However, by 1958, and despite the numerous reports on the roles of calcium and phosphorus in sheep rations, Pope still considered there was a "dearth of information in the literature on the Ca:P ratios required by sheep at different stages of production." During this period, copper deficiency was defined by Bennetts (1932) in Western Australia, cobalt deficiency was noted by 3 different groups of Australian researchers in 1935 (e.g., Underwood and Filmer, 1935), fluorine toxicity was described by Peirce (1939), molybdenum toxicity was demonstrated by Goss (1950), and selenium toxicity was identified by Beath et al. (1934). Numerous researchers demonstrated that sheep are capable of converting inorganic sulfur to sulfur-containing proteins (e.g., Starks et al., 1954).

Most of the vitamins were known by 1933, but very little work had been conducted before this date relative to the role of vitamins in sheep nutrition. Guilbert et al. (1937) reported that the vitamin A requirement was related to BW rather than energy and that it required 200 d to deplete the liver storage of ewe lambs previously pastured on green feed, proving the great ability sheep have to store this vitamin. These researchers also established that B vitamins are not required in rations fed to sheep because they are synthesized in adequate quantities by microorganisms in the rumen (e.g., McElroy and Goss, 1940). Many studies provided evidence that a cobalt deficiency manifests as a vitamin B_{12} deficiency. Smith et al. (1951) demonstrated the curative effect of vitamin B_{12} when administered to cobalt-deficient sheep. Andrews and Cunningham (1945) in New Zealand reported the daily requirement of lambs for vitamin D. In 1958, there was more interest in vitamin E and its role in white muscle disease (Willman et al., 1945) than in any other vitamin. These researchers showed that insufficient vitamin E was the cause of white muscle disease in lambs, but this finding was later disputed by other researchers (e.g., Muth, 1955). Pioneering work by Proctor et al. (1958), Muth et al. (1959), and Oldfield et al. (1960) showed that muscular dystrophy (stiff-lamb or white muscle disease) in lambs could be cured with selenium supplements (also confirmed by Hogue et al., 1962, and Paulson et al., 1968) and that incidences of white muscle disease were correlated with regions of the country with low forage selenium (Allaway and Hodgson, 1964). It was concluded that both vitamin E and selenium function as antioxidants and are essential nutrients that have sparing effects on the requirements of each other. The realization that selenium is an essential nutrient, and the subsequent approval by the US Food and Drug Administration (**FDA**) to use selenium as a dietary supplement, have had lasting impacts on the US sheep industry. The FDA published a final rule on August 25, 1997, that permitted the use of sodium selenate and sodium selenite in complete sheep feeds at a maximum concentration of 0.3 mg/kg. Before this date, the maximum approved concentration had been 0.1 mg/kg.

In the mid-1950s, following the trend in the swine and poultry sectors, numerous authors reported on the advantages of modifying the physical form of nutrients supplied to sheep. Neale concluded that the feed value of alfalfa (Neale, 1953) and low-quality hay (Neale, 1955) was improved by pelleting. The findings of Neale were confirmed by Cate et al. (1955) and numerous others, who also demonstrated the feasibility of using low-quality roughages as part of self-fed lamb fattening rations. In addition to pelleted rations resulting in increased intake, gains, and feed efficiency, their convenience ensured that pellets would have a lasting impact on the US sheep industry.

Although not a research document, the many editions of *Feeds and Feeding: A Handbook for the Student and Stockman* summarized information that influenced untold numbers of animal science students and future researchers. From 1900 to 1956, 22 editions of the book were authored and revised by W. A. Henry (editions 1 to 9), W. A. Henry and F. B. Morrison (editions 10 to 14), and F. B. Morrison (editions 15 to 22), with some assistance from E. B. Morrison (21 and 22) and S. H. Morrison (the 22nd and last edition).

In a special review, Jordan (1979) described changes that had occurred in the lamb feeding industry during the previous 50 yr. Changes in diet composition, feed processing, mineral supplementation, protein levels, feed additives, growth stimulants, and method of feeding all contributed to a 143% improvement in rate of gain and a 36% increase in feed utilization. Jordan also noted that in all but 2 of the previous 25 yr, grains were a lower cost source of dietary energy than roughages for feedlot operations. The use of high-concentrate diets was further made possible by the research results on calcium and phosphorus levels (Emerick and Embry, 1963) and the discovery that ammonium chloride in the diet also provides protection against urinary calculi (Crookshank et al., 1960). Diethylstilbestrol implants resulted in improved BW gains in feedlot lambs, and many researchers conducted studies with this and related compounds. However, the FDA prohibited diethylstilbestrol in 1979. Zeranol, a commercial estrogenic growth promoter, was shown to increase BW gain in feedlot lambs (e.g., Wilson et al., 1972). Although still available as an implant for lambs (and steers) in this country, the use of zeranol was banned by the European Union in 1985. Feedlot use of zeranol in lambs has declined because of the perceived association (by lamb feeders) with rectal prolapse.

Three related technologies that also were refined by researchers during this period and are still commonly used in the US sheep industry include creep feeding of lambs on rangelands and farms (e.g., Jordan and Gates, 1961), feeding of early-weaned lambs (e.g., Brothers and Whiteman, 1961), and feeding of very early weaned or orphaned lambs (e.g., Chiou and Jordan, 1973a,b,c,d; Pond et al., 1982). This latter technology has become particularly important to producers with intensive operations that have sheep with high prolificacy, predominantly the Finnsheep influence.

Nutrition research with sheep conducted in the past 100 yr has contributed to a wealth of knowledge that has been summarized numerous times (NRC, 1945, 1949, 1957, 1964, 1968, 1975, 1985), most recently in 2007 (NRC, 2007). Specific recommendations are presented for meeting the nutritional requirements of sheep—in terms of energy, protein, minerals, and vitamins (in the presence of adequate amounts of water) according to sex, age, and physiological stage of production—that represent our current state of knowledge. That information, coupled with access to computer programs capable of calculating low-cost feeding solutions, has had a major impact on how sheep are fed and on profitability in the sheep industry, particularly the lamb-feeding sector. To understand the effects on sheep of the infinite number of nutrient combinations to which they have been exposed, it is first necessary to understand the digestive physiology of the sheep. Many animal scientists and biologists have contributed to this task such that the roles of the rumen, reticulum, omasum, abomasum, and small and large intestines, and of nutrient metabolism and distribution are now quite well understood. Returning to the task at hand, which of the many nutrition-related developments have had a significant impact on the sheep industry?

The NE system for expressing feed values and animal requirements provides the most refined expression of the value of energy in a feedstuff and the energy requirements of animals. The evolution from using GE, to DE, to TDN, to ME, to NE_m and NE for growth and production has permitted progressive fine-tuning of rations for improved production and profitability. The NE system was first used in the cattle-feeding industry (Lofgreen and Garrett, 1968), and later a similar concept was applied to feeding lambs (Rattray et al., 1973). Similarly, protein content of a feedstuff was historically measured as CP, which did not take into account the quality of the protein (i.e., AA content, degradability in the rumen, and digestibility), but has now evolved to MP for growth, gestation, lactation, and fiber growth. From the viewpoint of the feed industry, information on MP is beginning to have an impact, because it is now being used by the more progressive feeders.

Antibiotics (e.g., chlortetracycline and oxytetracycline) added to the diet were shown to improve ADG and feed efficiency of lambs fed in confinement and also to reduce the number of unthrifty lambs (Hatfield et al., 1954; Benson, 2002). Antibiotics in feed also received FDA approval for reducing the incidence of vibrionic abortions and bacterial infections of the digestive tract (bacterial enteritis) and respiratory tract (bacterial pneumonia; Benson, 2002). An antibiotic in the grain supplement (60 mg/head per d of chlortetracycline) was shown to reduce lamb mortality when provided daily to the ewe 6 wk before and after lambing (Minyard, 1966). Recently, a perception has arisen that feeding livestock prophylactically with low levels of antibiotics has contributed to the observed increase in antibiotic-resistant strains of microorganisms in humans. Consequently, producers are under pressure from customers to stop feeding antibiotics to animals that may enter the human food chain.

Ionophores (lasalocid and decoquinate) added to the diet are also used in sheep production to improve the feed efficiency and growth rate (NRC, 2007). These compounds aid in the control of coccidiosis, decrease acidosis and bloat, and increase utilization of dietary N. Use of antibiotics and ionophores in the same feed is prohibited.

Native and improved pastures are a tremendous but historically underutilized resource in the United States. However, forage production on pasture can be uncertain, and even in times of plenty, domestic animals have been allowed to graze excessively in certain areas. The role of sheep grazing in natural resource management was the subject of a special issue of the *Sheep Research Journal* in 1994. Several nutrition-related topics (because sheep have to eat to make any of these things work!) were addressed in that issue that were important at the time, are more important now, and are expected to have an even greater impact in the future. These include the ecological advantage of multispecies grazing (Walker, 1994), and sheep grazing for sustainable agriculture (Ely, 1994), riparian and watershed management (Glimp and Swanson, 1994), range improvement (Havstad, 1994), enhancing wildlife habitat (Mosley, 1994), brush and fine fire fuel management (Taylor, 1994), silvicultural management (Sharrow, 1994), waste management (Glenn, 1994), and controlling rangeland weeds (Olson and Lacey, 1994). Much of the knowledge presented in these articles and much of the new technology generated on these topics since 1994 were captured in the recently published book *Targeted Grazing: A Natural Approach to Vegetation and Landscape Management*, edited by Launchbaugh et al. (2007). Sheep can utilize many plants that are either harmful to the plant community as a whole or that are avoided by or harmful to cattle. Frequent sheep-grazing provides a more economical alternative to chemical or mechanical methods. Plants that have been controlled successfully with sheep include leafy spurge (e.g., Olson and Wallander, 1998), spotted knapweed (e.g., Sheley et al., 2004), and cheatgrass (e.g., Mosley, 1996). On the other hand, many unexplained sheep deaths that occur in pastures and on rangeland are likely attributable to plant poisonings. It is often difficult to assess the overall economic losses attributable to poisonous plants because their ingestion by sheep is not always fatal. Loss of production can be caused by photosensitization, BW loss, abortion, and reproductive failure. When normal forages become scarce, plant poisonings typically increase. The identities of plants that are poisonous to sheep and symptoms exhibited by the poisoned animals have been well documented (e.g., Shulaw, 2002).

This leads to another topic that has received much attention from range nutrition researchers over the years, namely, range supplementation, a technology that continues to influence the sheep industry. To maintain and sustain animal productivity throughout the year, it is often necessary to provide supplementary feed at critical times (Shetaewi and Ross, 1987; Soder et al., 1995; Thomas and Kott, 1995). Knowing when to start supplementation, how much to provide, and of what composition the supplement should be have been the subject of many investigations. Range-monitoring tools (e.g., Kothmann and Hinnant, 1994) have been developed to answer the first question, and these produce estimates of the quantity and quality of forage per unit area currently being produced in the pasture. Having this information and making some assumptions about what the animals actually choose to eat from the variety of grasses, forbs, and bushes available, NRC (2007) recommended requirements could be used to calculate the theoretical composition of a supplementary ration. Other software is available to calculate the amounts and types of components that would produce the lowest cost supplement at a particular point (e.g., Montana State University, 2008). Researchers have concluded that sheep can be fed a protein supplement effectively as infrequently as one time per week (Huston et al., 1999).

Additionally, near-infrared reflectance spectroscopic techniques have been developed (Li et al., 2007) to estimate the diet composition of free-ranging livestock by using fecal analysis. Again, with this knowledge, deficiencies can be calculated and supplementation can be accurately tailored to meet the needs of the animal. Despite many years of research effort in this field, diet composition and intake of free-ranging animals are still very difficult to measure or predict. Stuth et al. (1999) suggested that the best way to predict diet selection and intake responses might be with computer-based simulations or decision-support tools.

Finally, research in the nutrition field that should not go unmentioned is the 20 yr of productivity recorded in the *Journal of Animal Science* by F. D. Provenza and colleagues (e.g., Burritt and Provenza, 1989; Villalba et al., 2008). Explanations for dietary preferences, aversions, and manipulations in sheep have been discovered and reported, and through application of the scientific approach, have helped to provide sheep producers with logical explanations for what sometimes appears to be random and unexplainable behavior of their livestock.

Management

Several management strategies have been developed and adopted by the industry to decrease lamb mortality caused by exposure, starvation, or disease. Shed lambing, the practice of bringing pregnant ewes indoors for a few days before and after parturition, is one such strategy (Inskeep, 2002). Restraining ewes in small enclosures (e.g., 1.2 × 1.2 m plywood pen) with their own lamb(s) for 3 d after parturition increases the likelihood of ewes accepting their lamb(s) and provides the lamb(s) with a warmer, less stressful environment. Keverne et al. (1983) described a method of fostering lambs that used vaginal stimulation of the ewe to simulate the birth of a lamb. This method apparently produces an immediate expression to alien lambs of the full complement of maternal behavior for up to several hours after delivery and is effective even in hormonally primed, nonpregnant ewes. Price et al. (1984a) reported that fostering of lambs initiated 2 to 3 d after parturition was successful in the majority of cases when the ewe was restrained in a small pen with the fostered lamb for 4 or more days, followed by a period of unrestrained cohabitation as a pair, and subsequent exposure to groups of females with young.

Price et al. (1984b) also described a relatively rapid, safe, and inexpensive method of fostering alien lambs that used a stockinette impregnated with the odor of one of the ewe's own lambs. Both of these methods are used by the industry to save lambs in situations in which a ewe has died after lambing or has produced more lambs than she can raise. These systems obviously require more labor than pasture lambing but have been necessary and cost effective, particularly in colder regions of the country. However, a current trend to circumvent the high labor requirement is to lamb in May, when the weather is not as harsh.

An alternative, but even more labor-intensive, plan to save lambs is to wean them at 2 or 3 d of age and raise them on milk replacer, changing to concentrate diets after 4 to 8 wk. This technology was reviewed by Large (1965) and Large and Penning (1967) and described by Peters and Heaney (1974). Removing the lambs at a very early age reduces the amount of high-quality diet required by the ewe, reduces predator and parasite problems, and enables the ewes to lamb more than once per year. Welch et al. (1963) discussed the advantages and possibilities of weaning lambs at this very early age as one component of an intensive production program. Heaney et al. (1980) summarized extensive Canadian research efforts for an intensive total confinement sheep production system. More recently, an experimental intensive lamb feeding system was described by Lupton et al. (2007), in which weaned lambs were fed to slaughter weight (59 kg) in an enclosed, raised-slatted floor facility, with the goal of producing exceptionally lean lamb and high-quality wool. During the past 30 yr, several large commercial ventures in North America (not including traditional feedlots) have attempted to use the technology developed for intensive, totally confined production systems, with varying degrees of success. Currently, Prairie Rose Lamb in Harlan, Iowa (http://www.naturallamb.biz/Templates/nl_news.htm; accessed April 28, 2008) is operating a commercial, highly intensive facility that uses covered, slatted pens housing 8,000 prolific crossbred ewes. It appears to be an excellent example of a commercial company that is attempting to use the best technology available to optimize income from lamb production by using a confined, intensive system.

Grazing management is the manipulation of animal grazing in the pursuit of a defined objective. Although not a top priority for many animal researchers, it has certainly been a high priority for some, as reflected by the numerous articles that have appeared in the *Journal of Animal Science* in the past 50 yr and as exemplified by Jordan and Wedin (1961) and Sharrow and Krueger (1979). The species most often studied in this context was cattle, followed by sheep and goats. However, the advantages of mixed-species grazing have also been alluded to (e.g., Abaye et al., 1994; Taylor, 1985). Although mixed-species grazing has been adopted widely in many areas, it is becoming increasingly apparent in Texas that management for deer, quail, and other wildlife is overshadowing grazing management for domestic livestock. Historically, sheep have been used to forage in diverse ecosystems, as discussed in the Nutrition Research section of this article. Intensively managed and rangeland grazing systems were presented by Lane and Huston (2002), whereas Launchbaugh et al. (2007) addressed targeted grazing management. Despite all the useful information generated to assist landowners to better manage their land, it is obvious that many have not or could not follow recommended practices. Degraded farm, pasture, and rangelands are the result. Too often, the livestock (sheep and goats, for example) are blamed by the public when the true culprit is the landowner who mismanages his resources.

Predation, especially by coyotes, remains one of the most serious problems facing the sheep industry. A special edition of the *Sheep and Goat Research Journal* (2004, vol. 19; Special Issue: Predation) was devoted to predation and contained 19 articles on various aspects of predation management. Millions of dollars have been spent researching nonlethal methods (e.g., night confinement, improved fencing, early weaning of lambs, selective removal of offending animals, and altering lambing dates) of controlling predation by coyotes (Wade, 1982; Shelton, 2004). Guardian animals such as dogs, donkeys, and llamas have been used in predation management programs with varying degrees of success, but losses caused by predation (by canines, felines, foxes, wild and feral swine, bears, raptors, raccoons, and other small mammals) have prematurely forced thousands of sheep producers out of business.

The current climate, in which federal legislation is being considered to ban some of the most effective means of controlling coyotes (Glass, 2008), in which domestic sheep are being prohibited from coming into contact with wild sheep (Talley, 2008), and in which sheep grazing is not being allowed on increasing areas of federal land, does not bode well for the future of the range-based sheep industry.

Marketing

Lamb marketing was the subject of a special issue of the *Sheep and Goat Research Journal* (1998, vol. 14, number 1; Special Issue: Lamb Marketing; 12 articles written by sheep research and extension personnel), in which a historical overview was provided by Bastian and Whipple (1998). In the western range states, approximately 60% of lambs are sold as feeders because of the early depletion of forage, whereas in the Midwest, most of the lambs traditionally have been weaned early, placed in a feedlot because of the availability of relatively inexpensive feed, and sold as slaughter lambs. This situation is likely to change in the near future because of the current very high price of corn and alternative feedstuffs. The marketing alternatives that have been available to producers for both lightweight and slaughter lambs have included direct negotiation between producer and feeder or packer, sale through middlemen to feedlots and packers, terminal markets, auction sales, special sales, electronic and video sales, and niche marketing directly to consumers. Lamb feedlots and packer (slaughter) and breaker plants have declined drastically in number since the 1950s because there are fewer lambs to slaughter and because of improved technology. Lamb meat is sold to (most) consumers by retailers. Retailers may receive their lamb directly from a packer or, more typically, from a breaker or a nonbreaking wholesaler (Williams and Davis, 1998). From the mid-1950s to the 1970s, the meat industry changed considerably as small butcher shops disappeared and more meat was shipped directly to supermarkets. Of course, the current trend is to ship prepackaged, prelabeled, ready-to-sell meat portions to supermarkets so that the only remaining role for the meat handler is to unpack the boxes and place the packages on shelves. Per capita consumption of lamb declined from 2.0 to 0.6 kg between 1961 and 1979, after which it has fluctuated between 0.6 and the present d 0.4 kg.

It is difficult to estimate the impact of animal science research on lamb marketing in the past 100 yr. Certainly, research has helped to produce larger lambs more efficiently, but many were undoubtedly delivered in an overfat condition (Tatum et al., 1989). The main reasons for this were marketing systems that rewarded producers primarily for BW in contrast to a value-based marketing system that would pay for consumable meat and usable hides. Even in recent times and at the recommendation of researchers and marketing specialists, several private companies and cooperatives have attempted to reward their producers by using value-based or "grid" marketing systems. Some may still be in existence, but notable others became financial failures and the status quo was essentially maintained.

Wool marketing begins at the shearing floor. The producer has the choice of placing whole fleeces from all his or her sheep directly in wool bags or bales (original bag system, the traditional method of selling raw wool) or removing inferior portions (skirting) and packaging the different fleece parts in separate lines according to estimated or measured quality characteristics (classing or grading). This latter practice is used predominantly in Australia but was shown to add value to US fine-wool clips (e.g., Lupton et al., 1992). Failure to perform practices and performing them poorly were shown to be 2 of the reasons US wools typically sold for less than similar wool grown in Australia (Hager, 2003), although there were additional issues such as colored fiber contamination in some US wools. However, the financial rewards of preparing wool in this manner are inversely proportional to the fineness of the wool, so are used less by producers of medium and coarse wools. An undetermined amount of wool is sold directly to textile mill agents, with fiber properties being estimated by the buyer or core-sample measurements being provided to him or her. However, most wool is transported to a central storage location (warehouse, cooperative, or pool) where it is offered for sale by a variety of techniques (e.g., private treaty, sealed-bid auction, or open auction), with the selling agent taking a commission. Bulk lots of wool in the United States are offered with and without objectively measured fiber characteristics (e.g., average fiber diameter and variability, clean yield, type and amount of vegetable matter contamination, average staple length and variability, and average staple strength and variability). Again, research has shown that providing buyers with objective measurements before a sale results in greater prices being offered (Lupton et al., 1993). In fact, this was well understood as early as the 1940s, when much of the technology for sampling and measuring the raw wool was developed in the United States (see Wool Research section). When the United States had a large wool textile industry and consumed all the domestically produced wool as well as great quantities of imported wool, wool was sold by many different methods. After the demise of this wool sector and the impending demise of the US textile industry as a whole, 75% of domestic wool is now sold to buyers representing overseas mills (R. Pope, Producers Marketing Cooperative Inc.; personal communication). This is causing the marketing system to conform more to international (Australian, New Zealand, and South African) standards. Specifically, the wool is shorn, skirted, classed, baled, and core-tested before sale. There are buyers for wool that is not prepared for sale in this fashion. These wool-handling companies buy the wool at discounted prices, unpack it, and then perform the previously mentioned processes to add value to the grease wool, at which point they can reoffer it to international buyers. As the sheep industry has declined, the number of storage and selling centers has also declined. At least one attempt has been made to conduct a central, open-bid sale representing wools from all areas of the country. For various reasons, this was not popular with the buyers and was discontinued. With declining quantities of wool being produced and increasing amounts being sold overseas, the time for this concept may be right. Perhaps this time, one of the port cities from which our wool is exported would provide the venue for a national sale.

Lamb Meat Research

Animal scientists, often in collaboration with meat scientists, have conducted a considerable number of studies with lamb meat that have been reported in the *Journal of Animal Science*. Many studies have evaluated the effects on carcass characteristics, palatability, and chemical composition of different breeds and crossbreeds. Similarly, the effects of sex, age, slaughter weight, diet, feed additives, production system, stress, and postslaughter treatments have been the subjects of many other reports. These studies have cumulatively been very helpful to US sheep producers, allowing them to make informed decisions concerning their choice of genetics and production systems.

Spencer (1928) was one of the earliest advocates for a uniform system for determining the quality of meat (and wool) in market lambs. The system he proposed to evaluate live lambs and carcasses was a refinement of the system in use commercially at the time. Some of the descriptors for the system sound quite familiar today—choice, good, medium, common, and cull—with the graders expressing their assessments to the nearest one-third of a grade. After new USDA grading standards for lamb were introduced in 1951, Kemp et al. (1953) conducted a study with blackface crossbred lambs that established the physical and chemical composition, energy values, and economy of carcasses and retail cuts by grade, which could have served as a model for many subsequent studies. In fact, official grade standards for lamb carcasses were changed 4 more times before 1983, and 2 of the changes (1969 and 1982) were a direct result of multiple academic cutability studies (Breidenstein and Carpenter, 1983). In 1964, an Industrywide Lamb and Wool Planning Committee produced a set of target specifications for "consumer-preferred lamb" to serve as a guide to lamb feeders, breeders, and researchers. The target ranges were BW (43.1 to 47.5 kg), yield (49 to 51%), quality grade (Choice), ribeye area (19.4 to 22.7 cm^2), leg (wide, deep, and heavily muscled), trimmed preferred cuts (70% of carcass weight), and fat covering (0.51 to 0.76 cm). Carpenter (1966) commented that producing uniform lambs to this specification that provided equal consumer satisfaction would be difficult because it was "evident that fatness and muscling of lamb carcasses differ a great deal due to differences in age, breed, carcass weight, sex, and treatment." He suggested that breeders and feeders should instead emphasize the single trait "weight of edible meat per day of age" (while still recognizing the importance of palatability), with only minor emphasis on the subjective estimates of conformation and quality.

Numerous studies have shown that ram lambs utilize feed more efficiently, grow faster, and produce leaner and more muscular carcasses than wethers. However, there has usually been some question about the palatability of meat from rams. Other studies have shown that heavy lambs tend to be fatter, have greater dressing percentages, and have a palatability similar to lighter lambs. Kemp et al. (1972) conducted a study with Hampshire crossbred lambs that agreed with the consensus of earlier findings but made the important point that although the ram meat was less palatable and was measurably tougher, it was still very acceptable. Despite this and many subsequent favorable studies with ram lambs, management problems in the feedlot and some difficulty with removing hides from some of the slaughtered rams have combined to ensure that large-scale lamb production with rams has not occurred in the United States.

Carse (1973) described a method for improving overall carcass quality and reducing the cold-toughening response by using temperature conditioning and electrical stimulation of the warm carcass. In the 1980s, this process was used on most New Zealand lamb destined for export (Parker and Pope, 1983) and was evaluated by numerous researchers in the United States (e.g., Riley et al., 1981). This technology was not adopted by the US sheep industry.

Melton (1990) reviewed the effects of feeds on the flavor of red meat, including lamb, and cited numerous studies demonstrating that some feeds (e.g., those containing rape, vetch, white clover, or soybean meal) gave rise to off-flavors in lamb. Most researchers reported that lambs fed concentrate diets alone produced meat with more acceptable flavor than lambs grazed on pasture alone, an exception being when the concentrate contained barley. In contrast, Hatfield et al. (2000) reported that wethers (ages 7 to 15 mo of age) fed either an 80% barley diet or finished on Montana rangeland produced acceptable carcasses with desirable meat palatability traits. Such studies have had an important impact on feeds used by lamb feeders in the past and obviously have important implications for the present time, with so many lamb feeders considering alternative feeding strategies because of substantial increases in concentrate prices.

Consumers have increasingly expressed concern about saturated fats and cholesterol in their diets. This has added momentum to the search for methods to produce leaner lambs while retaining the traditional attributes of fresh lamb. As Parker and Pope (1983) noted 25 yr ago, carcass improvement and lean-lamb technologies are available but have not been used to a great extent because producers are still being paid by BW and are mostly unable to participate in a value-based marketing system. Beermann et al. (1995) addressed this topic and observed that the US sheep industry had made very little progress to date in improving the composition of slaughter lambs. They explained that the low costs of BW gain because of inexpensive feed grains, a desire to increase the size of loin and rib cuts, the desire of the packers to slaughter heavier lambs, and the need to spread the supply of lamb throughout the year had all contributed to the increases in slaughter weights when, in fact, mature size and carcass composition should dictate the BW at which lambs are slaughtered. To avoid producing overfat lambs, their solutions were to use large mature-size terminal sires, feed rumen-escape dietary protein, feed intact males, and slaughter at an appropriate weight. Use of these strategies would permit lambs to be slaughtered at a younger age, which may improve meat quality. Coupled with an accelerated lambing system such as the Cornell STAR system (Hogue, 1987), the efficiency of lean lamb production could be increased further. It appeared for a while that lambs exhibiting the Callipyge phenotype had commercial potential for making a major contribution to the efficiency of producing lean lamb (Shackleford et al., 1998). These lambs have been shown to be superior to normal lambs in terms of feed efficiency, dressing percentage, and yield of retail cuts and would cost significantly less to produce (Busboom et al., 1999). Several approaches have been documented to mitigate the toughness of Callipyge lambs. To date, they have not been accepted by packers and have therefore not been available to many consumers.

Supplementation of lamb diets with safflower oil (up to 6% of the diets) resulted in increased amount of unsaturated fatty acids and CLA in the lean tissue without adversely affecting growth, carcass characteristics, and color stability of the meat (Boles et al., 2005). Increased content of CLA should translate to health benefits for the human consumer of the meat.

Wool Research

A search of the titles and abstracts of all articles published in the *Journal of Animal Science* from January 1910 to April 2008 by using the search term "wool" produced 330 articles, most of which were concerned with sheep's wool. Many of the studies were referred to in the Genetics and Nutrition Research sections, so this section is concerned mainly with advances in wool metrology. However, it should first be mentioned that a study reported by Reis and Schinckel (1961) demonstrated that abomasal infusion of casein or sulfur AA markedly increased wool growth. This gave rise to numerous additional studies that investigated protein metabolism in general, particularly those involving proteins capable of bypassing the rumen. Although these studies have not had a great impact on the US sheep industry in terms of increasing wool production, they have added immensely to our fundamental knowledge of wool (and hair) growth and protein metabolism.

Much of the early animal science research with wool was concerned with establishing procedures for estimating clean wool production of a flock (e.g., Jones and Lush, 1927) or of individual sheep (e.g., Hardy, 1933; Pohle et al., 1943; Sidwell et al., 1958) without shearing and washing the whole fleece. This eventually led to the procedure used today (Johnson and Larsen, 1978), in which the whole fleece is shorn and then subsampled with the aid of a coring machine. Sabbagh and Larsen (1978) were the first scientists to report that near-infrared reflectance spectroscopy had potential for estimating the clean yield and fiber diameter of grease wool fleeces. Despite much attention in the intervening years, this method has yet to receive the status of an official method of testing. Research documenting the evolution of core sampling from wool bags and bales was reported by numerous agricultural and textile researchers in this country and Australia. More recently, an automated grab sampler for bales was introduced, which retrieves random samples from within the bale that are then tested for length and strength. Researchers have evaluated follicle density, fiber fineness, variability (e.g., Burns, 1932; Pohle and Schott, 1943), and crimp (e.g., Hourihan et al., 1965) in the fleece by using methods involving calipers (e.g., Hill, 1922), a comparator (Pohle, 1940), projection microscopy (e.g., Kruegel, 1936), air flow (e.g., Anderson, 1954), a sonic tester (Reals, 1978), lasers (Lynch and Michie, 1976), and image analysis (Baxter et al., 1992; Qi et al., 1994; Brims et al., 1999). Many studies reported on the accuracy of different sampling protocols and measuring techniques for estimating the average fineness and variability in the fleece as a whole. We have learned that measuring representative samples obtained by core sampling the whole fleece results in the most accurate measurement, although estimates of fineness and clean fleece weight based on midside samples provide useful estimates and are used widely in animal fiber research. This work has influenced the sheep industry by providing the knowledge and techniques to accurately evaluate economically important wool traits, production, and value, which have been critical in genetic, selection, nutrition, management, breed and crossbreed evaluation and comparison, marketing, and processing studies. In addition, many histological and morphological studies have revealed how follicles are formed and begin to produce wool in the fetus (e.g., Ruttle and Sorenson, 1965) and throughout the life cycle of the sheep and have explained the physical and chemical structure of wool fibers, as well as the chemistry of the suint and wax coating them. This knowledge has assisted the textile industry in optimizing manufacturing processes to produce yarns and fabrics (Hunter, 1980) of the greatest possible quality and utility. Major processing trials conducted by Australian textile and wool scientists continue to have a major impact on the sheep industry throughout the world. These large-scale trials (Andrews et al., 1985; TEAM-3 Steering Comm., 2003), conducted in cooperation with many textile mills throughout the world, were concerned with predicting the physical properties of an intermediate textile structure (i.e., combed top that is later processed into yarn and fabrics) through a detailed knowledge of the raw materials (i.e., average fiber diameter and variability, comfort factor, clean yield, amount and type of vegetable matter contamination, staple length and variability, staple strength and variability, color, and crimp). With this knowledge, textile mills were better able to purchase wool to fit specific needs, and growers were informed how best to prepare, class, package, and measure wool before sale (e.g., Kott et al., 1992; Lupton et al., 1992) to optimize their income from wool and meet the requirements of the textile processors. Animal scientists in the United States conducted numerous studies to establish the economic impact to producers, warehouse operators, buyers, and textile mills of adopting these additional presale wool preparation and testing steps (e.g., Lupton et al., 1993). Once considered optional, these techniques have become a necessity because most US wool (approximately 75%) is now sold to overseas mills and must comply with international preparation and trading practices to be competitive with wool produced in other countries and to be eligible for sale in foreign markets.

The Future

After a long decline, the sheep population of the United States appears to have stabilized. I expect this trend to continue, with possible slow growth attributable to increasing numbers of the popular hairsheep, specialty wool breeds (for organic, superfine, and craft production), and milk sheep, and increased demand for lamb from the increasing ethnic population and young adults with large amounts of expendable income. I expect the current situation in the sheep industry to continue, with many producers having small to medium-sized flocks of sheep, relatively few producers running large, (relatively) low-input, extensive operations, and relatively few producers (individuals, coops, or corporations) operating large, high-input, intensive operations. Some breeders will participate in NSIP and will continue to make slow but steady progress within their breed. In addition, research (and extension) will be tailored at the various institutions to meet the needs of all. This research will be conducted in support of a domestic industry that has struggled with serious difficulties (some of which may not be researchable) for 60 yr or more. Many of the problems are specific to the sheep industry in the United States, whereas others are difficulties experienced by sheep and livestock producers throughout the world. This litany is well known in sheep circles, so I hesitate to belabor it here. However, it would seem necessary to understand the constraints so that research can be designed to overcome them where possible and provide practical information and technologies that will assist US sheep producers in remaining profitable. The list of threats and constraints includes the following:

- globalization and growing competition from sheep and textile industries in foreign countries in which lamb, wool, and textiles are being produced at a lower cost than in the United States;
- growing competition from aesthetically pleasing, functional, and cheaper synthetic fibers, accompanied by limited demand for wool (worldwide) and low per capita consumption of lamb meat in the United States;
- competition from other livestock species that may require less inputs and be more profitable than sheep (especially cattle and meat goats);
- competition from other meats that are being produced at less cost and that are perceived to contain less fat than lamb;
- relatively high labor costs in the United States and a shortage of laborers with sheep skills, especially shearers;
- changes in federal land use for recreational or controversial conservation causes that reduce the amount of grazing available to sheep;
- the increasing value of land, which decreases the opportunities for profitable sheep production;
- an increase in predation, which has technological solutions that cannot be used because of concerns by some segments of our society;
- similarly, real and perceived threats to endangered species that have been increasingly used to banish sheep grazing;
- the loss of infrastructure as the sheep industry has declined;
- contamination of wool with polypropylene fibers and with black and colored fibers from colored sheep, goats, cattle, and other animals, which undermines the acceptability of US wools in foreign markets;
- the perception by some consumers that chemical residues are contained in meat (growth hormones and antibiotics) and wool (insecticides);
- the misconception that all wool is itchy when worn next to the skin;
- the expectation of many young people to have more comfortable and prosperous lives than could reasonably be expected from raising sheep; and
- currently, the high and increasing costs of fuel and feed, which are making it extremely difficult to remain profitable in the sheep business.

It has been stated in the past that the ability of sheep to utilize a high proportion of renewable, lignocellulosic materials from diverse, often noncompetitive ecosystems should help the industry expand. It did not appear to help in the past 60 yr, but perhaps in this period of high grain and fuel prices, it will cause people to reconsider the type of livestock they want to use to make a living.

Some of the wool-related technologies that are expected to become mainstream in the sheep industry in the future have been close to mass acceptance for many years. These include robotic shearing (see pictorial review at http://www.mech.uwa.edu.au/jpt/shearmagic/autoshear.html; accessed April 28, 2008) and chemical defleecing (Lindahl et al., 1970; and later, Bioclip). With the shortage of shearers and with shearing prices in the range of $3 to $5 per ewe (and in excess of $15 for a fine-wool ram), the time for one or both of these technologies may finally have arrived. Less expensive measurement technologies for wool (e.g., near-infrared reflectance spectroscopy and automatic image analysis) will be refined to become acceptable to the wool industry and provide producers and marketers with less expensive fiber-testing options. A more substantial niche market will develop for specialty and extremely clean fleeces for hand spinners. With the demise of the wool-processing industry in the United States, people that craft textiles with their hands or with machines on a small scale may be the last true enthusiasts of wool left in the country. Although development of washable, shrink-proof wool was thought to be outside the realm of animal science in the past, altered genetics now promises us a direct route to this desirable product. Of course, the increasing presence of hairsheep in US flocks is not going to help the wool industry. However, once their numbers exceed a critical level to hold the interest of manufacturers, there appears to be considerable potential for their skins in the specialty leather market.

As prices of grain and other feedstuffs increase because of the global energy situation, sheep nutrition research may be dominated in the short-term with studies to optimize the feeding of by-products from the burgeoning biofuels industries. Conversely, it is likely that much emphasis will be placed on revamping production systems for growing grass-fattened lambs and systems in which lambs spend considerably less time in the feedlot. Lighter, less fat lambs might be more appealing to the current health-conscious segment of society. I also expect that the business of vegetation management and targeted grazing by using sheep (particularly to control fire hazards and to eat plants that are aversive to cattle) will experience considerable growth in the near term. Furthermore, grazing toxic or undesirable plants will be made more effective by selecting for improved genetics, using mixed-livestock grazing, and providing supplements designed to ameliorate the aversive effects of chemically defended invasive or toxic species.

Several technologies developed by meat researchers are expected to influence the industry in the near future. Methods for predicting lamb carcass fabrication yields (e.g., Cunha et al., 2004) and proportion of red meat (Brady et al., 2003) of warm carcasses have been evaluated by using video image analysis in real time. This technology appears to have the potential to predict carcass value accurately, a prerequisite to a value-based lamb marketing system. Although still not acceptable to many consumers, the increased safety of irradiated meat, including lamb, and the extended shelf life of such products are expected to make it more attractive to consumers. The development of more and tastier reconstituted, precooked, and easy-to-prepare lamb products is expected to increase their availability in stores and subsequent popularity. In addition, further refinement of atmospheric packaging for longer shelf life should result in increased use of this technology.

In the absence of a new family of effective anthelmintics being brought to the market, it appears to be necessary to refine production systems and nutrition to minimize losses to parasites. Producers will realize that some areas of the country are not suitable for sheep production. Administration of some naturally occurring products may also play a role in parasite control. It is apparent that further research is required to provide improvement for the problem of excessive perinatal deaths, which continue to undermine productivity in the sheep industry. With use of the live-animal and genetic tests available, it now appears possible that scrapie can be eliminated from the national flock.

In conclusion, it is emphasized that the future profitability of sheep production in the United States (and elsewhere in the world) will likely be determined by the success of research approaches that have received the lion's share of public and private funds for at least the past 15 yr (i.e., molecular genetics). In the sheep species session at the 2006 American Society of Animal Science annual meeting, we heard from 5 scientists concerning the application of genomics to sheep production. We learned that genomics had already delivered direct benefits to the industry by discovering the causative gene mutations for reproductive genes (Inverdale and Booroola) that have commercial application in certain production systems. We also learned that several sheep research programs around the world are attempting to identify additional gene mutations that are responsible for most of the phenotypes important in sheep production (i.e., fertility, reproduction, growth rate and efficiency, milk production, carcass quality and composition, wool characteristics, and disease resistance). The scope for delivery of highly significant benefits to the industry is enormous. Generally, there has been a slow rate of adoption of new technologies in the US sheep industry. I am optimistic that the expected benefits resulting from ongoing and future molecular genetics investigations will be so valuable and so readily incorporable into existing selection programs that even the most staid sheep producer in the country will be eager to take advantage of them.

At the end of the day, the goal should be a profitable, globally competitive, sustainable US sheep industry. Practices should be identified and technology developed to reduce our production costs to levels similar to or less than those in Australia, New Zealand, South Africa, and other sheep-producing countries (see Glimp, 1991, and Provenza, 2008, for more thought-provoking ideas on this and related subjects). We as researchers must develop technologies and producers should adopt technologies to make sheep products more desirable and more valuable to the consumer. In this endeavor, some government policies may have to be modified . . . but that is a discussion for another time.

LITERATURE CITED

Abaye, A. O., V. G. Allen, and J. P. Fontenot. 1994. Influence of grazing cattle and sheep together and separately on animal performance and forage quality. J. Anim. Sci. 72:1013–1022.

Afolayan, R. A., N. M. Fogarty, A. R. Gilmour, V. M. Ingham, G. M. Gaunt, and L. J. Cummins. 2008. Reproductive performance and genetic parameters in first cross ewes from different maternal genotypes. J. Anim. Sci. 86:804–814.

Ali, D. N., and D. R. Hennessy. 1996. The effect of level of feed intake on the pharmacokinetic disposition and efficacy of ivermectin in sheep. J. Vet. Pharmacol. Ther. 19:89–94.

Allaway, W. H., and J. F. Hodgson. 1964. Symposium on nutrition, forage, and pastures: Selenium in forages as related to geographic distribution of muscular dystrophy in livestock. J. Anim. Sci. 23:271–277.

Anderson, S. L. 1954. The air-flow method of measuring wool fibre fineness. J. Text. Inst. 45:312–316.

Andrews, E. D., and I. J. Cunningham. 1945. The vitamin D requirement of the sheep. N. Z. J. Sci. Technol. A 27:223–230.

Andrews, M. W., S. A. S. Douglas, A. H. M. Ireland, R. J. Quirk, and R. A. Rottenbury. 1985. Final Report. TEAM: Trials evaluating additional measurements. Australian Wool Corp., Melbourne, Australia.

Banks, R. G. 1990. LAMBPLAN: An integrated approach to genetic improvement for the Australian lamb industry. Proc. Aust. Assoc. Anim. Breed. Genet. 8:237–240.

Bastian, C. T., and G. D. Whipple. 1998. An historical overview of lamb marketing in the U.S. and considerations for the future. Sheep Goat Res. J. 14:4–15.

Baxter, B. P., M. A. Brims, and T. B. Taylor. 1992. Description and performance of the Optical Fibre Diameter Analyser (OFDA). J. Text. Inst. 83:507–526.

Baylis, M., and W. Goldmann. 2004. The genetics of scrapie in sheep and goats. Curr. Mol. Med. 4:385–396.

Beath, O. A., J. A. Draize, and C. S. Gilbert. 1934. Plants poisonous to livestock. Wyoming Exp. Sta. Bull. 200:1–84.

Beermann, D. H., T. F. Robinson, and D. E. Hogue. 1995. Impact of composition manipulation on lean lamb production in the United States. J. Anim. Sci. 73:2493–2502.

Beever, J. E., and A. D. Markey. 2006. Molecular tools for sheep breeding: DNA-based markers for monogenic traits and QTL. J. Anim. Sci. 84(Suppl. 1):158. (Abstr.)

Bennetts, H. W. 1932. Enzootic ataxia of lambs in Western Australia. Aust. Vet. J. 11:84–92.

Benson, M. E. 2002. Nutrition. Pages 701–747 in SID Sheep Production Handbook. American Sheep Industry Association, ed. Am. Sheep Ind. Assoc., Centennial, CO.

Bidwell, C., and N. Cockett. 2006. Genomic regions associated with sheep muscle and carcass traits. J. Anim. Sci. 84:159. (Abstr.)

Boles, J. A., R. W. Kott, P. G. Hatfield, J. W. Bergman, and C. R. Flynn. 2005. Supplemental safflower oil affects the fatty acid profile, including conjugated linoleic acid, of lamb. J. Anim. Sci. 83:2175–2181.

Boughton, I. B., and W. T. Hardy. 1934. Contagious ecthyma (sore mouth) of sheep and goats. J. Am. Vet. Med. Assoc. 85:150–178.

Boylan, W. J., Y. M. Berger, and C. E. Allen. 1976. Carcass merit of Finnsheep crossbred lambs. J. Anim. Sci. 42:1413–1420.

Brady, A. S., K. E. Belk, S. B. LeValley, N. L. Dalsted, J. A. Scanga, J. D. Tatum, and G. C. Smith. 2003. An evaluation of the lamb vision system as a predictor of lamb carcass red meat yield percentage. J. Anim. Sci. 81:1488–1498.

Breidenstein, B. C., and Z. L. Carpenter. 1983. The red meat industry: Product and consumerism. J. Anim. Sci. 57:119–132.

Brims, M. A., A. D. Peterson, and S. G. Gherardi. 1999. Introducing the OFDA2000—For rapid measurement of diameter profile on greasy wool staples. Techn. Rep. RWG 04. Int. Wool Text. Org., Florence, Italy.

Brothers, D. G., and J. V. Whiteman. 1961. Influence of early weaning on creep-fed milk lambs when weaned on weight or age. J. Anim. Sci. 20:420–425.

Burns, R. H. 1932. Fleece analysis in sheep. J. Anim. Sci. 1932:246–258.

Burritt, E. A., and F. D. Provenza. 1989. Food aversion learning: Conditioning lambs to avoid a palatable shrub (*Cercocarpus montanus*). J. Anim. Sci. 67:650–653.

Busboom, J. R., T. I. Wahl, and G. D. Snowder. 1999. Economics of callipyge lamb production. J. Anim. Sci. 77:243–248.

Campbell, F. 2008. Texas Rambouillet Superior Genetics flock in 10th year. Ranch Rural Living. 89:25–27.

Campbell, K. H., J. McWhir, W. A. Ritchie, and I. Wilmut. 1996. Sheep cloned by nuclear transfer from a cultured cell line. Nature 380:64–66.

Carpenter, Z. L. 1966. What is consumer-preferred lamb? J. Anim. Sci. 25:1232–1235.

Carse, W. A. 1973. Meat quality and the acceleration of post-mortem glycolysis by electrical stimulation. Int. J. Food Sci. Technol. 8:163–166.

Casas, E., B. A. Freking, and K. A. Leymaster. 2004. Evaluation of Dorset, Finnsheep, Romanov, Texel, and Montadale breeds of sheep: II. Reproduction of F_1 ewes in fall mating seasons. J. Anim. Sci. 82:1280–1289.

Casas, E., B. A. Freking, and K. A. Leymaster. 2005. Evaluation of Dorset, Finnsheep, Romanov, Texel, and Montadale breeds of sheep: V. Reproduction of F_1 ewes in spring mating seasons. J. Anim. Sci. 83:2743–2751.

Cate, H. A., J. M. Lewis, R. J. Webb, M. E. Mansfield, and U. S. Garrigus. 1955. The effect of pelleting rations of varied quality on feed utilization by lambs. J. Anim. Sci. 14:137–142.

Chiou, P. W. S., and R. M. Jordan. 1973a. Ewe milk replacer diets for young lambs. I. Effect of age of lamb and dietary fat on digestibility of the diet, nitrogen retention and plasma constituents. J. Anim. Sci. 36:597–603.

Chiou, P. W. S., and R. M. Jordan. 1973b. Ewe milk replacer diets for young lambs. II. Some effects of environmental temperature and dietary fat level on growth and feed utilization of young lambs. J. Anim. Sci. 36:604–606.

Chiou, P. W. S., and R. M. Jordan. 1973c. Ewe milk replacer diets for young lambs. III. Effect of age of lambs and dietary protein and fat levels on the body composition of young lambs. J. Anim. Sci. 36:607–612.

Chiou, P. W. S., and R. M. Jordan. 1973d. Ewe milk replacer diets for young lambs. IV. Protein and energy requirements of young lambs. J. Anim. Sci. 37:581–587.

Cockett, N., and J. Beever. 2001. Screening for the molecular defect causing spider lamb syndrome in sheep. US Patent No. 6,306,591 Bl.

Cockett, N. E., T. S. Hadfield, C. H. Wu, and K. Nomura. 2006. Resources available for sheep genomics research. J. Anim. Sci. 84:158. (Abstr.)

Cockett, N. E., T. L. Shay, J. E. Beever, D. Nielsen, J. Albretsen, M. Georges, K. Peterson, A. Stephens, W. Vernon, O. Timofeevskaia, S. South, J. Mork, A. Maciulis, and T. D. Bunch. 1999. Localization of the locus causing spider lamb syndrome to the distal end of ovine chromosome 6. Mamm. Genome 10:35–38.

Coop, R. L., and I. Kyriazakis. 1999. Nutrition-parasite interaction. Vet. Parasitol. 84:187–204.

Crookshank, H. R., F. E. Keating, E. Burnett, J. H. Jones, and R. E. Davis. 1960. Effect of chemical and enzymatic agents on the formation of urinary calculi in fattening steers. J. Anim. Sci. 19:595–600.

Cunha, B. C. N., K. E. Belk, J. A. Scanga, S. B. LeValley, J. D. Tatum, and G. C. Smith. 2004. Development and validation of equations utilizing lamb vision system output to predict lamb carcass fabrication yields. J. Anim. Sci. 82:2069–2076.

Davis, G. P., and S. K. DeNise. 1998. The impact of genetic markers on selection. J. Anim. Sci. 76:2331–2339.

Dickerson, G. E. 1977. Crossbreeding evaluation of Finnsheep and some US breeds for market lamb production. North Central Reg. Publ. No. 246. USDA and Univ. Nebraska, Lincoln.

Dickerson, G. E., H. A. Glimp, and K. E. Gregory. 1975. Genetic resources for efficient meat production in sheep: Preweaning viability and growth of Finnsheep and domestic crossbred lambs. J. Anim. Sci. 41:43–53.

Dixon, A. B., M. Knights, J. L. Winkler, D. J. Marsh, J. L. Pate, M. E. Wilson, R. A. Dailey, G. Seidel, and E. K. Inskeep. 2007. Patterns of late embryonic and fetal mortality and association with several factors in sheep. J. Anim. Sci. 85:1274–1284.

Ely, D. G. 1994. The role of grazing sheep in sustainable agriculture. Sheep Res. J. (Special Issue) 10:37–51.

Emerick, R. J., and L. B. Embry. 1963. Calcium and phosphorus levels related to the development of phosphate urinary calculi in sheep. J. Anim. Sci. 22:510–513.

Ercanbrack, S. K., and A. D. Knight. 1998. Responses to various selection protocols for lamb production in Rambouillet, Targhee, Columbia, and Polypay sheep. J. Anim. Sci. 76:1311–1325.

Feary, E. S., J. L. Juengel, P. Smith, M. C. French, A. R. O'Connell, S. B. Lawrence, S. M. Galloway, G. H. Davis, and K. P. McNatty. 2007. Patterns of expression of messenger RNAs encoding *GDF9, BMP15, TGFBR1, BMPR1B,* and *BMPR2* during follicular development and characterization of ovarian follicular populations in ewes carrying the Woodlands $FecX2^W$ mutation. Biol. Reprod. 77:990–998.

Fischer, T. M. 2006. SheepGenomics—An integrated gene discovery program. J. Anim. Sci. 84(Suppl. 1):159. (Abstr.)

Fitzhugh, H. A., and G. E. Bradford, ed. 1983. Hair Sheep of Western Africa and the Americas: A Genetic Resource for the Tropics. Westview Press, Boulder, CO.

Fogarty, N. M. 1995. Genetic parameters for live weight, fat and muscle measurements, wool production and reproduction in sheep: A review. Anim. Breed. Abstr. 63:101–143.

Foote, R. H. 2002. The history of artificial insemination: Selected notes and notables. J. Anim. Sci. 80:1–10.

Fraps, G. S. 1918. Mineral Requirements of Sheep. Bull. 232. Texas Agric. Exp. Sta., College Station.

Fraps, G. S., and V. L. Cory. 1940. Composition and utilization of range vegetation of Sutton and Edwards counties. Bull. 586. Texas Agric. Exp. Sta., College Station.

Freetly, H. C., and K. A. Leymaster. 2004. Relationship between litter birth weight and litter size in six breeds of sheep. J. Anim. Sci. 82:612–618.

Freking, B. A., J. W. Keele, C. W. Beattie, S. M. Kappes, T. P. L. Smith, T. S. Sonstegard, M. K. Nielsen, and K. A. Leymaster. 1998. Evaluation of the ovine callipyge locus: I. Relative chromosomal position and gene action. J. Anim. Sci. 76:2062–2071.

Freking, B. A., and K. A. Leymaster. 2004. Evaluation of Dorset, Finnsheep, Romanov, Texel, and Montadale breeds of sheep: IV. Survival, growth and carcass traits of F_1 lambs. J. Anim. Sci. 82:3144–3153.

Freking, B. A., K. A. Leymaster, and L. D. Young. 2000. Evaluation of Dorset, Finnsheep, Romanov, Texel, and Montadale breeds of sheep: I. Effects of ram breed on productivity of ewes of two crossbred populations. J. Anim. Sci. 78:1422–1429.

Glass, L. 2008. TSGRA fighting 1080, M-44 ban. Ranch Rural Living 89(4):19.
Glenn, J. S. 1994. The role of sheep and sheep products in waste management. Sheep Res. J. (Special Issue) 10:113–115.
Glimp, H. A. 1991. Can we produce lamb for $0.40 per pound? Pages 35–42 in Proc. Sheep Forage Prod. Systems Symp., Steamboat Springs, CO. Sheep Industry Development Program, Englewood, CO.
Glimp, H. A., and S. R. Swanson. 1994. Sheep grazing and riparian and watershed management. Sheep Res. J. (Special Issue) 10:65–71.
Goss, H. 1950. Excess molybdenum in forage in certain localities in California. Proc. Soil Sci. Soc. Fla. 10:175–177.
Guilbert, H. R., R. F. Miller, and E. H. Hughes. 1937. The minimum vitamin A and carotene requirement of cattle, sheep and swine. J. Nutr. 13:543–564.
Hager, S. D. 2003. Determining price differences among different classes of wool from the U.S. and Australia. MS Thesis. Texas A&M Univ., College Station.
Hardy, J. I. 1933. A simple method of determining clean-wool yield and density of fleeces. J. Anim. Sci. 1933:234–238.
Harris, L. E., and H. H. Mitchell. 1941a. The value of urea in the synthesis of protein in the paunch of the ruminant. I. In maintenance. J. Nutr. 22:167–182.
Harris, L. E., and H. H. Mitchell. 1941b. The value of urea in the synthesis of protein in the paunch of the ruminant. II. In growth. J. Nutr. 22:183–196.
Hatfield, E. E., U. S. Garrigus, and H. W. Norton. 1954. Antibiotic supplements in rations for growing and fattening lambs. J. Anim. Sci. 13:715–725.
Hatfield, P. G., R. A. Field, J. A. Hopkins, and R. W. Kott. 2000. Palatability of wethers fed an 80% barley diet processed at different ages and of yearling wethers grazed on native range. J. Anim. Sci. 78:1779–1785.
Havstad, K. M. 1994. Sheep grazing as a range improvement tool. Sheep Res. J. (Special Issue) 10:72–78.
Hazel, L. N. 1943. The genetic basis for constructing selection indexes. Genetics 28:476–490.
Hazel, L. N., and C. E. Terrill. 1945. Heritability of weaning weight and staple length in range Rambouillet lambs. J. Anim. Sci. 4:347–358.
Hazel, L. N., and C. E. Terrill. 1946. The construction and use of a selection index for range Rambouillet lambs. J. Anim. Sci. 5:412. (Abstr.)
Heaney, D. P., L. Ainsworth, T. R. Batra, P. S. Fiser, A. J. Hackett, G. A. Langford, and A. J. Lee. 1980. Research for an intensive total confinement sheep production system. Tech. Bull. No. 2. Agric. Can. Anim. Res. Inst., Can. Dept. Agric., Ottawa, Canada.
Hill, J. A. 1922. Micrometer calipers for teaching the discrimination of the fineness of wool. J. Anim. Sci. 1922:8–11.
Hogue, D. E. 1987. Frequent lambing systems. Pages 57–63 in New Techniques in Sheep Production. I. F. M. Marai and J. B. Owen, ed. Butterworths, London, UK.
Hogue, D. E., J. F. Proctor, R. G. Warner, and J. K. Loosli. 1962. Relation of selenium, vitamin E and an unidentified factor to muscular dystrophy (stiff-lamb or white muscle disease) in the lamb. J. Anim. Sci. 21:25–29.
Hourihan, M. E., W. R. Harvey, and C. E. Terrill. 1965. Evaluation of a method of measuring staple crimp of grease locks from individual fleeces. J. Anim. Sci. 24:5–8.
Hulet, C. V., S. K. Ercanbrack, and A. D. Knight. 1984. Development of the Polypay breed. J. Anim. Sci. 58:15–24.
Hulet, C. V., H. P. Voightlander, A. L. Pope, and L. E. Casida. 1956. The nature of early-season infertility in sheep. J. Anim. Sci. 15:607–616.
Hunter, L. 1980. The effects of wool fibre properties on processing performance and yarn and fabric properties. Pages 133–193 in Proc. 6th Int. Wool Text. Res. Conf., Pretoria, South Africa.
Huston, J. E., B. S. Engdahl, and K. W. Bales. 1999. Supplemental feeding interval for adult ewes. Sheep Goat Res. J. 15:87–93.
Ingle, W. 1910. Sheep-feeding experiments in Britain. Trans. Highl. Agric. Soc. Scotland 22:178–258.
Inskeep, K. 2002. Reproduction. Pages 901–940 in SID Sheep Production Handbook. American Sheep Industry Association, ed. Am. Sheep Ind. Assoc., Centennial, CO.
Isler, B. J., B. A. Freking, R. M. Thallman, M. P. Heaton, and K. A. Leymaster. 2006. Evaluation of associations between prion haplotypes and growth, carcass, and meat quality traits in a Dorset × Romanov sheep population. J. Anim. Sci. 84:783–788.
Johnson, B. C., T. S. Hamilton, H. H. Mitchell, and W. B. Robinson. 1942. The relative efficiency of urea as a protein substitute in the rations of ruminants. J. Anim. Sci. 1:236–245.
Johnson, C. L., and S.-A. Larsen. 1978. Clean wool determination of individual fleeces. J. Anim. Sci. 47:41–45.
Johnson, P. L., J. C. McEwan, K. G. Dodds, R. W. Purchas, and H. T. Blair. 2005. Meat quality traits were unaffected by a quantitative trait locus affecting leg composition traits in Texel sheep. J. Anim. Sci. 83:2729–2735.
Jones, J. M., and J. L. Lush. 1927. Methods of selecting wool samples in shrinkage studies. J. Anim. Sci. 1927:115–117.
Jordan, R. M. 1979. Fifty years of lamb feeding: A special review. Feedstuffs 51:133, 202.
Jordan, R. M., and C. E. Gates. 1961. Effect of grain feeding the ewe and lamb on subsequent lamb growth. J. Anim. Sci. 20:809–811.
Jordan, R. M., and W. F. Wedin. 1961. Effect of grazing management on body weight and subsequent wool and lamb production of non-lactating ewes. J. Anim. Sci. 20:883–885.
Kaplan, R. M., J. M. Burke, T. H. Terrill, J. E. Miller, W. R. Getz, S. Mobini, E. Valencia, M. J. Williams, L. H. Williamson, M. Larsen, and A. F. Vatta. 2004. Validation of the FAMACHA eye color chart for detecting clinical anemia in sheep and goats on farms in the southern United States. Vet. Parasitol. 123:105–120.
Kellner, O. 1908. The Scientific Feeding of Animals. Duckworth Press, London, UK.
Kemp, J. D., S. Bull, and H. W. Bean. 1953. The economy and nutritive value of different cuts of lamb of different grades. J. Anim. Sci. 12:338–346.
Kemp, J. D., J. M. Shelley Jr., D. G. Ely, and W. G. Moody. 1972. Effects of castration and slaughter weight on fatness, cooking losses and palatability of lamb. J. Anim. Sci. 34:560–562.
Keverne, E. B., F. Levy, P. Poindron, and D. R. Lindsay. 1983. Vaginal stimulation: An important determinant of maternal bonding in sheep. Science 219:81–83.
Klosterman, E. W., M. L. Buchanan, D. W. Bolin, and F. M. Bolin. 1951. Levels and sources of protein in rations for pregnant ewes. J. Anim. Sci. 10:257–265.
Kothmann, M. M., and R. T. Hinnant. 1994. The Grazing Manager, Version 1.0. Software Manual. Texas Agric. Exp. Sta., College Station.
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.
Kruegel, E. O. 1936. Wool top standards. Text. Res. J. 6:465–480.
Lane, W., and E. Huston. 2002. Forages. Pages 201–223 in SID Sheep Production Handbook. American Sheep Industry Association, ed. Am. Sheep Ind. Assoc., Centennial, CO.
Large, R. V. 1965. The artificial rearing of lambs. J. Agric. Sci. 65:101–108.
Large, R. V., and P. D. Penning. 1967. The artificial rearing of lambs on cold reconstituted whole milk and on milk substitute. J. Agric. Sci. 69:405–409.
Laughlin, A. M., D. F. Waldron, B. F. Craddock, G. R. Engdahl, R. K. Dusek, J. E. Huston, C. J. Lupton, D. N. Ueckert, T. L. Shay, and N. E. Cockett. 2003. Use of DNA markers to determine paternity in a multiple-sire mating flock. Sheep Goat Res. J. 18:14–17.
Launchbaugh, K., J. Walker, and R. Daines. 2007. Targeted grazing—A natural approach to vegetative management and landscape enhancement. Am. Sheep Ind. Assoc., Centennial, CO.

Leymaster, K. 2002. Fundamental aspects of crossbreeding of sheep: Use of breed diversity to improve efficiency of meat production. Sheep Goat Res. J. 17:50–58.

Li, H., D. Tolleson, J. Stuth, K. Bai, F. Mo, and S. Kronberg. 2007. Faecal near infrared reflectance spectroscopy to predict diet quality for sheep. Small Rumin. Res. 68:263–268.

Lindahl, I. L. 1966. Detection of pregnancy in sheep by means of ultrasound. Nature 212:642–643.

Lindahl, I. L., E. H. Dolnick, and C. E. Terrill. 1970. Chemical defleecing of sheep under field conditions. J. Anim. Sci. 31:947–949.

Linklater, K. A., and M. C. Smith. 1993. Color atlas of diseases and disorders of the sheep and goat. Wolfe Publishing/Mosby-Year Book Europe Ltd., London, UK.

Lofgreen, G. P., and W. N. Garrett. 1968. A system for expressing net energy requirements and feed values for growing and finishing beef cattle. J. Anim. Sci. 27:793–806.

Loosli, J. K., H. H. Williams, W. E. Thomas, F. H. Ferris, and L. A. Maynard. 1949. Synthesis of amino acids in the rumen. Science 110:144–146.

Lupton, C. J., B. A. Freking, and K. A. Leymaster. 2004. Evaluation of Dorset, Finnsheep, Romanov, Texel, and Montadale breeds of sheep: III. Wool characteristics of F_1 ewes. J. Anim. Sci. 82:2293–2300.

Lupton, C. J., J. E. Huston, B. F. Craddock, F. A. Pfeiffer, and W. L. Polk. 2007. Comparison of three systems for concurrent production of lamb meat and wool. Small Rumin. Res. 72:133–140.

Lupton, C. J., F. A. Pfeiffer, and N. E. Blakeman. 1993. Economic impact of pre-sale fiber measurements on prices paid for wool. SID Sheep Res. J. 9:35–37.

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.

Lush, J. L. 1937. Animal Breeding Plans. 1st ed. Collegiate Press, Ames, IA.

Lynch, L. J., and N. A. Michie. 1976. An instrument for the rapid automatic measurement of fibre fineness distribution. Text. Res. J. 46:653–660.

Malpaux, B., C. Viguie, D. C. Skinner, J. C. Thiery, J. Pelletier, and P. Chemineau. 1996. Seasonal breeding in sheep: Mechanism of action of melatonin. Anim. Reprod. Sci. 42:109–117.

Marshall, F. R. 1949. The making of the Columbia sheep. Natl. Wool Grower 39:9–11.

Martin, G. B., C. M. Oldham, Y. Cognie, and D. T. Pearce. 1986. The physiological responses of anovulatory ewes to the introduction of rams—A review. Livest. Prod. Sci. 15:219–247.

McElroy, L. W., and H. Goss. 1940. A quantitative study of vitamins in the rumen contents of sheep and cows fed vitamin-low diets I. riboflavin and vitamin K. J. Nutr. 20:527–540.

McKellar, Q. A. 2006. The health of the sheep industry and the medicines to maintain it. Small Rumin. Res. 62:7–12.

McNatty, K. P., N. L. Hudson, L. Whiting, K. L. Reader, S. Lun, A. Western, D. A. Heath, P. Smith, L. G. Moore, and J. L. Juengel. 2007. The effects of immunizing sheep with different BMP15 or GDF9 peptide sequences on ovarian follicular activity and ovulation rate. Biol. Reprod. 76:552–560.

Melton, S. L. 1990. Effects of feeds on flavor or red meat: A review. J. Anim. Sci. 68:4421–4435.

Mendel, G. 1865. Experiments in plant hybridization (English translation). http://www.mendelweb.org/Mendel.html Accessed June 17, 2008.

Meyer, H. H. 1985. Breed differences in ovulation rate and uterine efficiency and their contribution to fecundity. Pages 185–191 in Genetics of Reproduction in Sheep. R. B. Land and D. W. Robinson, ed. Butterworths, London, UK.

Meyer, J. H., and W. C. Weir. 1954. The tolerance of sheep to high intakes of sodium chloride. J. Anim. Sci. 13:443–449.

Min, B. R., and S. P. Hart. 2003. Tannins for suppression of internal parasites. J. Anim. Sci. 81 (E Suppl.):E102–E109.

Minyard, J. A. 1966. Influence of antibiotics on lamb livability and performance. J. Anim. Sci. 25:591. (Abstr.)

Mosley, J. C. 1994. Prescribed sheep grazing to enhance wildlife habitat on North American rangelands. Sheep Res. J. (Special Issue) 10:79–91.

Mosley, J. C. 1996. Prescribed sheep grazing to suppress cheatgrass: A review. Sheep Goat Res. J. 12:74–80.

Montana State University. 2008. Montana State University Sheep Ration Program. http://www.msusheepration.montana.edu Accessed June 16, 2008.

Muth, O. H. 1955. White muscle disease (myopathy) in lambs and calves I. Occurrence and nature of the disease under Oregon conditions. J. Am. Vet. Med. Assoc. 126:355–361.

Muth, O. H., J. E. Oldfield, J. R. Schubert, and L. F. Remmert. 1959. White muscle disease (myopathy) in lambs and calves. VI. Effects of selenium and vitamin E on lambs. Am. J. Vet. Res. 20:231–234.

NRC. 1945. Recommended Nutrient Allowances for Sheep. No. 5. Natl. Acad. Sci., Washington, DC.

Neale, P. E. 1953. Alfalfa cube mixture for fattening lambs and wethers. Bull. 375. New Mexico Agric. Exp. Sta., Las Cruces.

Neale, P. E. 1955. Alfalfa cube mixture for fattening lambs. Bull. 398. New Mexico Agric. Exp. Sta., Las Cruces.

Notter, D. R. 1998. The US National Sheep Improvement Program: Across-flock genetic evaluations and new trait development. J. Anim. Sci. 76:2324–2330.

Notter, D. R. 2000. Potential for hair sheep in the United States. J. Anim. Sci. 77:1–8.

Notter, D. R., S. P. Greiner, and M. L. Wahlberg. 2004. Growth and carcass characteristics of lambs sired by Dorper and Dorset rams. J. Anim. Sci. 82:1323–1328.

NRC. 1949. Recommended Nutrient Allowances for Sheep. No. 5. Natl. Acad. Sci., Washington, DC.

NRC. 1957. Nutrient Requirements of Domestic Animals. No. 5. Nutrient Requirements of Sheep. Publ. 504. Natl. Acad. Sci., Washington, DC.

NRC. 1964. Nutrient Requirements of Domestic Animals. No. 5. Nutrient Requirements of Sheep. Publ. 1193. Natl. Acad. Sci., Washington, DC.

NRC. 1968. Nutrient Requirements of Domestic Animals. No. 5. Nutrient Requirements of Sheep. 4th ed. Publ. 1963. Natl. Acad. Sci., Washington, DC.

NRC. 1975. Nutrient Requirements of Domestic Animals. No. 5. Nutrient Requirements of Sheep. 5th ed. Natl. Acad. Sci., Washington, DC.

NRC. 1985. Nutrient Requirements of Domestic Animals. No. 5. Nutrient Requirements of Sheep. 6th ed. Natl. Acad. Press, Washington, DC.

NRC. 2007. Nutrient Requirements of Small Ruminants. Sheep, Goats, Cervids, and New World Camelids. Natl. Acad. Press, Washington, DC.

O'Rourke, K. I., T. V. Baszler, T. E. Besser, J. M. Miller, R. C. Cutlip, G. A. H. Wells, S. J. Ryder, S. M. Parish, A. N. Hamir, N. E. Cockett, A. Jenny, and D. P. Knowles. 2000. Preclinical diagnosis of scrapie by immunohistochemistry of third eyelid lymphoid tissue. J. Clin. Microbiol. 38:3254–3259.

Oldfield, J. E., O. H. Muth, and J. R. Schubert. 1960. Selenium and vitamin E as related to growth and white muscle disease in lambs. Proc. Soc. Exp. Biol. Med. 102:799–801.

Olson, B. E., and J. R. Lacey. 1994. Sheep: A method for controlling rangelands weeds. Sheep Res. J. (Special Issue) 10:105–112.

Olson, B. E., and R. T. Wallander. 1998. Effects of sheep grazing on a leafy spurge-infested Idaho fescue community. J. Range Manage. 51:247–252.

Parker, C. F., and A. L. Pope. 1983. The U.S. sheep industry: Changes and challenges. J. Anim. Sci. 57(Suppl. 2):75–99.

Paulson, G. D., G. A. Broderick, C. A. Baumann, and A. L. Pope. 1968. Effect of feeding sheep selenium fortified trace mineralized salt: Effect of tocopherol. J. Anim. Sci. 27:195–202.

Peirce, A. W. 1939. Observations on the toxicity of fluorine for sheep. Counc. Sci. Ind. Res. Aust. Bull. 121:1–35.

Peters, H. F., and D. P. Heaney. 1974. Factors influencing the growth of lambs reared artificially or with their dams. Can. J. Anim. Sci. 54:9–18.

Pohle, E. M. 1940. The application of a rapid comparator method for determining fineness and variability in wool. J. Anim. Sci. 1940:161–168.

Pohle, E. M., and R. G. Schott. 1943. Wool fineness in eight sampling regions on yearling Rambouillet ewes. J. Anim. Sci. 2:197–208.

Pohle, E. M., H. W. Wolf, and C. E. Terrill. 1943. Clean wool yield variation among regions of Rambouillet fleeces. J. Anim. Sci. 2:181–187.

Pond, W. G., C. L. Ferrell, T. G. Jenkins, and L. D. Young. 1982. Weaning of lambs to a dry diet at ten days of age. J. Anim. Sci. 55:1284–1292.

Pope, A. L. 1958. Fifty years of progress in sheep nutrition. J. Anim. Sci. 17:1015–1028.

Price, E. O., M. Dunbar, and M. R. Dally. 1984a. Behavior of ewes and lambs subjected to restraint fostering. J. Anim. Sci. 58:1084–1089.

Price, E. O., G. C. Dunn, J. A. Talbot, and M. R. Dally. 1984b. Fostering lambs by odor transfer: The substitution experiment. J. Anim. Sci. 59:301–307.

Proctor, J. F., D. E. Hogue, and R. G. Warner. 1958. Selenium, vitamin E, and linseed oil meal as preventatives of muscular dystrophy in lambs. J. Anim. Sci. 17:1183. (Abstr.)

Provenza, F. D. 2008. What does it mean to be locally adopted and who cares anyway? J. Anim. Sci. 86(E. Suppl.):E271–E284.

Qi, K., C. J. Lupton, F. A. Pfeiffer, and D. L. Minikheim. 1994. Evaluation of the optical fibre diameter analyser (OFDA) for measuring fiber diameter parameters of sheep and goats. J. Anim. Sci. 72:1675–1679.

Rattray, P. V., W. N. Garrett, N. Hinman, I. Garcia, and J. Castillo. 1973. A system for expressing the net energy requirements and net energy content of feeds for young sheep. J. Anim. Sci. 36:115–122.

Reals, C. A. 1978. Sonic fineness testing of scoured ½-inch wool cores for average fiber diameter. Text. Res. J. 48:300–302.

Reis, P. J., and P. G. Schinckel. 1961. Nitrogen utilisation and wool production by sheep. Aust. J. Agric. Res. 12:335–352.

Riley, R. R., J. W. Savell, G. C. Smith, and M. Shelton. 1981. Improving appearance and palatability of meat from ram lambs by electrical stimulation. J. Anim. Sci. 52:522–529.

Ruttle, J. L., and A. M. Sorenson Jr. 1965. Prenatal development of the wool follicles in Rambouillet sheep. J. Anim. Sci. 24:69–75.

Sabbagh, H. R., and S. A. Larsen. 1978. Wool yield by infrared reflection analysis. Proc. West. Sect. Am. Soc. Anim. Sci. 29:108–109.

Safari, A., and N. M. Fogarty. 2003. Genetic parameters for sheep production traits: Estimates from the literature. Tech. Bull. 49. NSW Agric., Orange, Australia.

Sakul, H., and W. J. Boylan. 1992. Evaluation of U.S. sheep breeds for milk production and milk composition. Small Rumin. Res. 7:195–201.

Salamon, S. 1967. Observations on fertility of ram semen frozen by different methods. Aust. J. Exp. Agric. Anim. Husb. 7:559–561.

Sellner, E. M., J. W. Kim, M. C. McClure, K. H. Taylor, R. D. Schnabel, and J. F. Taylor. 2007. Applications of genomic information in livestock. J. Anim. Sci. 85:3148–3158.

Shackleford, S. D., T. L. Wheeler, and M. Koohmaraie. 1998. Can the genetic antagonisms of callipyge lamb be overcome? Proc. Recip. Meat Conf. 51:125–132.

Sharrow, S. H. 1994. Sheep as a sulvicultural management tool in temperate conifer forest. Sheep Res. J. (Special Issue) 10:97–104.

Sharrow, S. H., and W. C. Krueger. 1979. Performance of sheep under rotational and continuous grazing on hill pastures. J. Anim. Sci. 49:893–899.

Sheley, R. L., J. S. Jacobs, and J. M. Martin. 2004. Integrating 2,4-D and sheep grazing to rehabilitate spotted knapweed infestations. J. Range Manage. 57:371–375.

Shelton, M. 1979. Estimation of genetic change in a performance testing program for sheep. J. Anim. Sci. 48:26–31.

Shelton, M. 2004. Predation and livestock production: Perspective and review. Sheep Goat Res. J. 19:2–5.

Shelton, M., J. C. Miller, W. T. Magee, and W. T. Hardy. 1954. A summary of four years work in ram progeny and performance testing. J. Anim. Sci. 13:215–228.

Shetaewi, M. M., and T. T. Ross. 1987. Effect of supplementation with concentrates and lasalocid during late pregnancy and lactation on productivity of Rambouillet ewes and development of wool follicles in their lambs. J. Anim. Sci. 65:351–358.

Shulaw, W. 2002. Health. Pages 401–486 in SID Sheep Production Handbook. American Sheep Industry Association, ed. Am. Sheep Ind. Assoc., Centennial, CO.

Sidwell, G. M., and L. R. Miller. 1971a. Production in some pure breeds of sheep and their crosses. I. Reproductive efficiency in ewes. J. Anim. Sci. 32:1084–1089.

Sidwell, G. M., and L. R. Miller. 1971b. Production in some pure breeds of sheep and their crosses. II. Birth weights and weaning weights in lambs. J. Anim. Sci. 32:1090–1094.

Sidwell, G. M., and L. R. Miller. 1971c. Production in some pure breeds of sheep and their crosses. III. Production indexes in ewes. J. Anim. Sci. 32:1095–1098.

Sidwell, G. M., P. E. Neale, and G. L. Jessup Jr. 1958. A comparison of five methods of estimating clean fleece weight. J. Anim. Sci. 17:593–597.

Sidwell, G. M., R. L. Wilson, and M. E. Hourihan. 1971. Production in some pure breeds of sheep and their crosses. IV. Effect of crossbreeding on wool production. J. Anim. Sci. 32:1099–1102.

Slen, S. B., and F. Whiting. 1955. Wool and lamb production as affected by the source of protein in the ration of the mature ewe. J. Anim. Sci. 14:844–859.

Smith, B. 2006. 2006 West Virginia Ram Performance Test Summary. News Ewe Can Use. http://www.caf.wvu.edu/avs/sheep/pdf/nlfall06.pdf Accessed June 9, 2008.

Smith, S. E., B. A. Koch, and K. L. Turk. 1951. The response of cobalt-deficient lambs to liver extract and vitamin B_{12}. J. Nutr. 44:455–464.

Snowder, G. D. 2001. Characteristics of the American Polypay: A review. Anim. Genet. Resour. Inf. 29:19–30.

Snowder, G. D., and S. L. Duckett. 2003. Evaluation of the South African Dorper as a terminal sire breed for growth, carcass, and palatability characteristics. J. Anim. Sci. 81:368–375.

Snowder, G. D., C. J. Lupton, J. M. Shelton, R. W. Kott, G. E. Bradford, M. R. Dally, A. D. Knight, H. A. Glimp, J. N. Stellflug, P. J. Burfening, and P. V. Thompson. 1997. Comparison of U.S. fine-wool breeds and Australian Merino F_1 crosses. I. Wool characteristics and body weight. Sheep Goat Res. J. 13:108–115.

Soder, K. J., V. M. Thomas, R. W. Kott, P. G. Hatfield, and B. Olson. 1995. Influence of energy or protein supplementation during midpregnancy on forage intake of ewes grazing Montana winter range. J. Anim. Sci. 73:2853–2859.

Spencer, D. A. 1928. A method of determining quality in the wool and meat of market lambs. J. Anim. Sci. 1928:163–167.

Starks, P. B., W. H. Hale, U. S. Garrigus, R. M. Forbes, and M. F. James. 1954. Response of lambs fed varied levels of elemental sulfur, sulfate sulfur, and methionine. J. Anim. Sci. 13:249–257.

Stellflug, J. N., N. E. Cockett, and G. S. Lewis. 2006. Relationship between sexual behavior classifications of rams and lambs sired in a competitive breeding environment. J. Anim. Sci. 84:463–468.

Stuth, J. W., M. Freer, H. Dove, and R. K. Lyons. 1999. Nutritional management for free-ranging livestock. Pages 696–751 in Nutritional Ecology of Herbivores. H. J. G. Jung and G. C. Fahey, ed. Am. Soc. Anim. Sci., Savoy, IL.

Talley, B. 2008. Bighorn, domestic sheep disease conflict discussed at symposium. Sheep Ind. News 12:12–13.

Tatum, J. D., J. W. Savell, H. R. Cross, and J. G. Butler. 1989. A national survey of lamb carcass cutability traits. SID Res. J. 5:23–31.

Taylor, C. A., Jr. 1985. Multispecies grazing research overview—Texas. Pages 65–83 in Proc. Conf. Multispecies Grazing. F. H. Baker and R. K. Jones, ed. Winrock Int. Inst. Agric. Dev. Morrilton, AR.

Taylor, C. A., Jr. 1994. Sheep grazing as brush and fine fire fuel management tool. Sheep Res. J. (Special Issue) 10:92–96.

TEAM-3 Steering Committee. 2003. TEAM-3 processing trial update. Wool Technol. Sheep Breed. 51(2):176–191.

Terrill, C. E. 1937. Measurement of reproductive capacity as an aid in selection of rams of high fertility. Pages 311–331 in Proc. 30th Annu. Mtg. Am. Soc. Anim. Prod., Chicago, IL.

Terrill, C. E. 1947. Breed crosses in the development of the Targhee sheep. J. Anim. Sci. 6:83–92.

Terrill, C. E. 1958. Fifty years of progress in sheep breeding. J. Anim. Sci. 17:944–959.

Terrill, C. E., and L. N. Hazel. 1943. Heritability of yearling fleece and body traits of range Rambouillet ewes. J. Anim. Sci. 2:358–359. (Abstr.)

Thomas, D. L. 2004. Overview of the dairy sheep sector in Canada and the United States. Proc. 10th Great Lakes Dairy Sheep Symp., Hudson, WI. http://www.ansci.wisc.edu/Extension-New%20copy/sheep/Publications_and_Proceedings/symposium_04/pdf%20of%20Dairy%20Sheep%20Proceedings/complete2004proceedings.pdf Accessed Aug. 22, 2008.

Thomas, D. L., Y. M. Berger, and B. C. McKusick. 2001. Effects of breed, management system, and nutrition on milk yield and milk composition of dairy sheep. J. Anim. Sci. 79(E Suppl.):E16–E20.

Thomas, D. L., and A. R. Cobb. 1986. Inheritance of spider syndrome in Suffolk sheep. J. Anim. Sci. 63(Suppl. 1):195–196.

Thomas, D. L., D. F. Waldron, G. D. Lowe, D. G. Morrical, H. H. Meyer, R. A. High, Y. M. Berger, D. D. Clevenger, G. E. Fogle, R. G. Gottfredson, S. C. Loerch, K. E. McClure, T. D. Willingham, D. L. Zartman, and R. D. Zelinsky. 2003. Length of docked tail and the incidence of rectal prolapse in lambs. J. Anim. Sci. 81:2725–2732.

Thomas, V. M., and R. W. Kott. 1995. A review of Montana winter range ewe nutrition research. Sheep Goat Res. J. 11:17–24.

Thonney, M. L., P. A. Martinez-Hernandez, J. B. Taylor, and D. L. Thomas. 2008. Sheep symposium: Biology and management of low-input lambing in easy-care systems. J. Anim. Sci. 86 (E Suppl.):E244–E245.

Trinidad, R. 2007. Future breed genetics determined at central performance tests. Sheep Ind. News November:11, 15.

Underwood, E. J., and J. F. Filmer. 1935. The determination of the biologically potent element (cobalt) in limonite. Aust. Vet. J. 11:84–92.

USDA, Agricultural Research Service. 1962. Status of the screwworm in the United States. Special Rep. ARS 22-79. USDA, Agric. Res. Serv., Washington, DC.

Vanimisetti, H. B., S. P. Greiner, A. M. Zajac, and D. R. Notter. 2004. Performance of hair sheep composite breeds: Resistance of lambs to *Haemonchus contortus*. J. Anim. Sci. 82:595–604.

Villalba, J. J., F. D. Provenza, and J. O. Hall. 2008. Learned appetites for calcium, phosphorus, and sodium in sheep. J. Anim. Sci. 86:738–747.

Wade, D. A. 1982. Impacts, incidence and control of predation on livestock in the United States, with particular reference to predation by coyotes. Special Publ. No. 10. Counc. Agric. Sci. Technol., Ames, IA.

Waldron, D. F., and C. J. Lupton. 2008. Improvement of sheep through selection of performance-tested and progeny-tested breeding animals. Res. Center Tech. Rep. 2008-1. Texas AgriLife Res., College Station, TX.

Walker, J. W. 1994. Multispecies grazing: The ecological advantage. Sheep Res. J. (Special Issue) 10:52–64.

Watson, R. H., and H. M. Radford. 1960. The influence of rams on onset of oestrus in Merino ewes in the spring. Aust. J. Agric. Res. 11:65–71.

Welch, J. G., G. W. Vander Noot, and R. L. Gilbreath. 1963. Effect of feeding milk replacers with varying amounts of fat for hothouse lamb production. J. Anim. Sci. 22:155–158.

Wheeler, M. B. 2003. Production of transgenic livestock: Promise fulfilled. J. Anim. Sci. 81:32–37.

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

Williams, G. W., and E. E. Davis. 1998. Lamb market structure. Sheep Goat Res. J. 14:16–34.

Willingham, T., M. Shelton, and C. J. Lupton. 1988. The influence of introducing the Booroola Merino genotype to Rambouillet flocks on reproduction and fleece traits in comparison with other selected breed crosses. Sheep Ind. Dig. Res. J. 4:1–5.

Willman, J. P., J. K. Loosli, S. A. Adsell, F. B. Morrison, and P. Olafson. 1945. Prevention and cure of muscular stiffness ("stiff-lamb" disease) in lambs. J. Anim. Sci. 4:128–132.

Wilson, D. E., and D. G. Morrical. 1991. The National Sheep Improvement Program: A review. J. Anim. Sci. 69:3872–3881.

Wilson, L. L., H. Varela-Alvarez, M. C. Rugh, and M. L. Borger. 1972. Growth and carcass characters of rams, cryptorchids, wethers, and ewes subcutaneously implanted with zeranol. J. Anim. Sci. 34:336–338.

Wilson, T. 2006. How genomics will continue to improve productivity for the New Zealand sheep sector. J. Anim. Sci. 84(Suppl. 1):158. (Abstr.)

Wilson, T., X. Y. Wu, J. L. Juengel, I. K. Ross, J. M. Lumsden, E. A. Lord, K. G. Dodds, G. A. Walling, J. C. McEwan, A. R. O'Connell, K. P. McNatty, and G. W. Montgomery. 2001. Highly prolific Booroola sheep have a mutation in the intracellular kinase domain of bone morphogenetic protein IB receptor (ALK-6) that is expressed in both oocytes and granulosa cells. Biol. Reprod. 64:1225–1235.

Wolff, E. 1874. Farm Foods. Gurney and Jackson, London, UK.

Wright, S. 1921. Systems of mating I. The biometric relations between parent and offspring. Genetics 6:111–123.