Evaluation of Rambouillet, Polypay, and Romanov–White Dorper × Rambouillet ewes mated to terminal sires in an extensive rangeland production system: body weight and wool characteristics[1,2]

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ABSTRACT: Though lamb sales account for the majority of annual receipts on U.S. sheep operations, wool is an important income source for many Western flocks. Crossing fine-wool sheep with prolific or composite hair sheep breeds can increase lamb production, but fleece quality and marketability may be reduced by a greater content of nonwool fibers (e.g., med and kemp). The objectives of this study were to compare BW and wool characteristics of Rambouillet, Polypay, and Romanov–White Dorper × Rambouillet (RW-RA) ewes under extensive rangeland management conditions. Ewe BW was collected before mating (fall) and 30 d postlambing (spring) each year from 1 yr up to 4 yr of age. In spring and fall, Rambouillet and Polypay ewes were similar in BW ($P \geq 0.94$). Spring BW did not differ ($P = 0.13$) between RW-RA and Polypay, but Rambouillet ewes were heavier than RW-RA in the spring ($P = 0.02$). Both Rambouillet and Polypay ewes were heavier ($P < 0.07$) than RW-RA in the fall. Greasy fleece weight and mid-side wool samples were collected from ewes at 1 and 4 yr of age. Clean fleece weights (CFW) were estimated from average laboratory scoured yield of mid-side wool samples composited within-breed. Average fiber diameter (AFD), SD of fiber diameter (SD-FD), and percentage med (%M), kemp (%K), and total medullated fibers (%T) were quantified on individual mid-side wool samples. There was no difference in 1-yr-old CFW among breed types ($P \geq 0.96$). Four-yr-old Rambouillet ewes had heavier CFW (2.29 kg; $P < 0.001$) than 4-yr-old Polypay (1.83 kg) and RW-RA ewes (1.86 kg), which were not different ($P > 0.99$). Within 1- and 4-yr-olds, AFD differed among breed type ($P < 0.001$) and was the finest for Rambouillet (20.1 and 21.9 µm, respectively), intermediate for RW-RA (22.8 and 24.8 µm), and coarsest for Polypay (24.2 and 26.7 µm). Also within 1- and 4-yr olds, SD-FD was lowest in

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Rambouillet, intermediate in Polypay, and greatest in RW-RA ($P < 0.01$). Wool from RW-RA ewes had greater %M, %K, and %T ($P < 0.001$) than wool from Rambouillet and Polypay ewes, which were not different ($P > 0.99$). Results indicated superior wool production for Rambouillet compared with the coarser, more variable wool produced by Polypay and RW-RA. Still, past research reported greater lamb production in Polypay and RW-RA ewes which, under recent market conditions, would be associated with greater annual gross revenue for these breed types than for Rambouillet.

Key words: body weight, fleece characteristics, medullated fibers, sheep, wool

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INTRODUCTION

Wool is an important income source, alleviating seasonality of cash-flow for the extensively managed operations prevalent in the Western states even though receipts from its sale represented just 5–13% of the total revenue for the average U.S. sheep producer from 2010 to 2015 (LMIC, 2016). Within fine-wool and dual-purpose sheep breeds, advances in husbandry practices and technology aimed at enhancing wool quality should be considered in tandem with improving lamb production. Crossbreeding designs using rams from prolific breeds (e.g., Finnsheep and Romanov) and traditional Western white-faced ewe breeds (e.g., Targhee and Rambouillet) have increased the number and weight of lamb weaned per ewe (Thomas and Whiteman, 1979; Thomas, 2010). Similarly, crossbreeding with composite hair sheep breeds has increased lamb production and survival (Bunge et al., 1995; Notter et al., 2017). However, the marketability of half-hair sheep fleeces is limited by its greater content of medullated fiber, which reduces the quality of woolen products (Bunge et al., 1996). Romanov–White Dorper × Rambouillet (**RW-RA**) ewes were generated at the USDA, U.S. Sheep Experiment Station (**USSES**; Dubois, ID) and managed as contemporaries with Polypay and Rambouillet ewes from 2009 to 2015. Notter et al. (2017) reported that RW-RA ewes had greater cumulative numbers (5.9 lambs) and weight (153 kg) of lambs weaned over their productive lives than Polypay (4.9 lambs and 123 kg, respectively) and Rambouillet ewes (2.9 lambs and 99 kg, respectively). However, information regarding other economically important characteristics of these breed types is not known and merits investigation. Thus, the objectives of this study were to quantify and compare BW and wool characteristics of Rambouillet, Polypay, and RW-RA ewes managed under extensive rangeland conditions at the USSES.

MATERIALS AND METHODS

The USSES Institutional Animal Care and Use Committee (**IACUC**) approved all husbandry practices and experimental procedures used in this study (IACUC numbers 0905 and 1105).

Animals and Management

A detailed description of the establishment and management of the breed types evaluated in the present study was provided by Notter et al. (2017, 2018). Briefly, the Rambouillet, Polypay, and RW-RA ewes were born from 2009 to 2011. Ewes for this study were generated by mating USSES Rambouillet ewes to 1 of 7 Rambouillet rams or 1 of 7 Romanov × White Dorper rams and mating USSES Polypay ewes to 1 of 7 Polypay rams, all in single-sire breeding pens. Most rams were used for only one yr, but one Polypay ram was used in a second year and, in total, 20 Polypay, 21 Rambouillet, and 21 Romanov × White Dorper rams were represented. All Romanov × White Dorper rams originated from the U.S. Meat Animal Research Center (Clay Center, NE). One Rambouillet and one Polypay ram originated from USSES flocks, and the remainder were sampled from 20 and 18 industry flocks, respectively. Industry Rambouillet and Polypay breeders were asked to provide 1- to 2-yr-old rams that they considered to be representative of the breed.

Thus, ewes evaluated in the present study were either purebred Rambouillet, purebred Polypay, or ¼ Romanov × ¼ White Dorper × ½ Rambouillet (i.e., **RW-RA**). Ewes of these breed types were exposed to terminal rams (Suffolk, Columbia, Suffolk × Columbia, or Columbia × Suffolk) for

21 d beginning in mid-October. Ewe lambs were exposed to rams for the first time at 7–8 mo of age and retained for up to four production cycles. Following mating, adult ewes were managed together and grazed on winter range until mid to late January when they were transferred to a feedlot before lambing. Ewe lambs were managed in a feedlot from the end of breeding until they lambed. Following lambing, all ewes were bonded with their lamb(s) in individual pens for 24 h then transferred to a feedlot where they remained for approximately 1 mo. Ewes that produced triplet or smaller litters were required, with only a few exceptions, to attempt to rear all their lambs. During feedlot management, ewes received a total mixed ration designed to meet or exceed their nutrient requirements for the corresponding production stage. Yearling and adult ewes and their lambs were managed together and grazed sagebrush steppe or subalpine forest from late April until weaning in July or August after which ewes returned to grazing until breeding. Ewes were only removed from the study if they became functionally unsound (Notter et al., 2018).

Ewe BW was collected in early September before the start of mating (fall) and in mid-April (spring). Ewes were sheared in mid-February of each year, approximately 4 wk before parturition. A full staple mid-side wool sample (~30 g) was collected from ewes 1 wk before their first and fourth yearly shearing. At shearing, bellies were removed, and pre-skirted fleeces were weighed to obtain greasy fleece weight (**GFW**) at 1 and 4 yr of age. Mid-side wool samples were sent to the Montana Wool Laboratory at Montana State University (Bozeman, MT) where objective measurements of fiber traits were obtained. Average laboratory scoured yield (ASTM, 1990a) was quantified on a subset of wool samples composited across ages and within breed type (n = 15 per breed type) to estimate clean fleece weight (**CFW**) for each individual. Yield estimated from whole-fleece core samples would have been ideal to capture individual variation, and this is a limitation of the present study. However, this quantity of wool was not available at the time of fiber analyses. Nevertheless, others have determined yield from mid-side wool samples when estimating nutritional (Thompson and Hynd, 1998; De Barbieri et al., 2015) and genetic effects (Mortimer and Atkins, 1989; Wuliji et al., 2001) on wool production in sheep.

Mid-side wool samples were cut with a guillotine to produce approximately 2-mm fiber snippets which were washed and analyzed on an Optical-based Fibre Diameter Analyser 2000 (OFDA; BSC Electronics Pty. Ltd., Attadale, Western Australia). The fiber metrology traits of interest reported by the OFDA2000 included average fiber diameter (**AFD**), SD of fiber diameter (**SD-FD**), CV of fiber diameter (**CV-FD**), comfort factor (**CF**; percentage of individual fibers < 30 μm in diameter), and mean fiber curvature (**CRV**). All measurements were obtained using standard International Wool Textile Organization protocols (IWTO, 2013).

Med (e.g., hair) and kemp fibers lack crimp, are generally coarser than true wool fibers, and are characterized by having a central canal (i.e., medulla) containing cell residues and air pockets. These nonwool fibers can be collectively referred to as "medullated fibers." A random subset of mid-side wool samples (n = 128), balanced across breed type, age, and ewe birth year, were sent to the Bill Sims Wool and Mohair Research Laboratory (San Angelo, TX) where numbers of medullated fibers in 10,000 total fibers were quantified using an OFDA100 (BSC Electronics Pty. Ltd.; ASTM, 1990b; IWTO, 2000). By this method, a fiber was considered to be medullated (i.e., med or kemp) if its opacity was greater than 80% and its diameter greater than the sample AFD. Kemp fibers had opacities greater than 94% and diameters coarser than 25 μm. Med fiber content was then designated as total medullated fiber content minus kemp fiber content (Lupton and Pfeiffer, 1998). The final response variables were percentage med (%M), kemp (%K), and total medullated (%T) fibers in each mid-side wool sample.

Statistical Analysis—Ewe BW

Initial models characterized effects of reproductive status on ewe BW in spring and fall. Ewes were assigned to 1 of 3 outcome groups to discriminate among those that 1) did not lamb (n = 284), 2) lambed but did not wean any lambs (n = 160), and 3) weaned at least one lamb (n = 1,672). The model included fixed effects of outcome group, ewe birth year (2009, 2010, or 2011), breed type, ewe age (1 through 4 yr), and all two-way interactions among these variables, and was fitted separately for spring and fall BW using the GLM procedure of SAS (v9.4; SAS Inst. Inc., Cary, NC). Because of large effects of outcome group on ewe BW and considerable imbalance among frequencies of the different outcome classes among breed types and ages, characterization of differences in BW among breed types was subsequently described after deleting spring and fall weights of ewes that did not wean at least one lamb in a given calendar year.

The model for this analysis included fixed effects of season (spring vs. fall), ewe birth year, breed type, age, all two-way interactions among these variables, and the ewe birth year × age × breed type and ewe birth year × age × season three-way interactions. The latter interactions were included because they incorporated lambing year × breed type and lambing year × season interaction effects. This model also included random effects of sire of the ewe (nested within breed type and birth year) and individual ewe (nested within sire of the ewe, ewe birth year, and breed type) and was fitted using the MIXED procedure of SAS. The final model investigated the effects of number of lambs born (**NLB**) and weaned (**NLW**) on ewe BW by adding these fixed effects to the previous mixed model. For this analysis, the effects of ewe age were partitioned into effects of age class (yearling vs. adult) and age nested within age class. The effect of NLB was nested within the age class effect to account for the absence of triplet and quadruplet litters in yearling ewes. Adult ewes that produced litters of three or four were combined into a single class (3+), and the effect of NLW was nested within the age class × NLB interaction effect.

Statistical Analysis—Wool Characteristics

Fleece weights (GFW and CFW; n = 1,067) and fiber metrology traits (AFD, SD-FD, CV-FD, CF, and CRV; n = 1,075) were analyzed using the MIXED procedure and included the fixed effects of ewe birth year, breed type, and age (1 or 4 yr) and random effects of sire of the ewe (nested within ewe birth year and breed type) and individual ewe (nested within sire of the ewe, ewe birth year, and breed type). Spring BW at 1 or 4 yr was fit as a linear covariate for the analysis of GFW and CFW. Because of subsampling (n = 128), individual ewes did not have multiple %M, %K, and %T records and these traits were analyzed using the GLM procedure with the fixed effects of ewe birth year, breed type, and age. All possible two-way interactions in these models were tested and subsequently removed from the final model if they were not significant (P > 0.05).

RESULTS

Ewe BW

The first model included data on ewes that did not lamb (i.e., were open), lambed but failed to wean any lambs, and weaned at least one lamb to determine the effect of reproductive status on ewe BW in spring and fall. Open ewes and ewes that failed to wean a lamb did not differ in mean BW in spring (63.5 ± 0.93 and 63.1 ± 0.83 kg, respectively; P = 0.92) or fall (75.9 ± 0.88 and 76.7 ± 0.76 kg, respectively; P = 0.80). However, both were heavier (P ≤ 0.01) in spring and fall than ewes that weaned a lamb (60.7 ± 0.20 and 69.1 ± 0.18 kg, respectively).

Next, only data for ewes that weaned at least 1 lamb was analyzed across seasons and significant ewe birth year × age, ewe birth year × season, age × season, and breed type × season interaction effects were detected (P ≤ 0.01). However, the main effects or interaction effects involving ewe birth year are not discussed because annual variation in performance is expected but difficult to attribute to specific environmental effects. Therefore, comparisons of means among ages and breed types were made within a season (Table 1). As expected, ewes weighed less in spring, following lambing, and during early lactation, than in fall, after weaning their lambs and at the start of the subsequent mating season. Ewe BW differed (P < 0.001) between all ages within spring and fall. Within both spring

Table 1. Least squares means and greatest SE of BW for the season × age and season × breed type interaction effects of Rambouillet (RA), Polypay (PP), and Romanov–White Dorper × Rambouillet (RW-RA) ewes that weaned at least one lamb

			Ewe BW, kg		
Effect	Class	n	Spring	Fall	Greatest SE
Age, yr	1	340	50.6[d]	60.2[d]	0.62
	2	500	57.5[c]	68.1[c]	0.58
	3	454	64.6[b]	72.6[b]	0.59
	4	378	68.3[a]	74.4[a]	0.59
Breed type	RA	441	62.2[a]	70.2[a,b]	1.12
	PP	573	60.9[a,b]	69.9[a]	0.90
	RW-RA	658	57.7[b]	66.3[b]	0.90

[a–d]Means within a season and age and within a season and breed type with no superscript in common differ (P ≤ 0.05) using the Tukey–Kramer mean separation procedure.

and fall, Rambouillet and Polypay ewes were similar in BW ($P \geq 0.94$). Spring BW did not differ ($P = 0.13$) between RW-RA and Polypay, but Rambouillet ewes were heavier than RW-RA in the spring ($P = 0.02$). Both Rambouillet and Polypay ewes were heavier ($P < 0.07$) than RW-RA in the fall. Seasonal differences in BW were smaller for less-prolific Rambouillet ewes (8.0 kg) than for more prolific RW-RA (8.6 kg) and Polypay (9.0 kg). Younger (1- and 2-yr-old) ewes gained more BW between spring and fall (9.6 and 10.6 kg, respectively) than did older (3- and 4-yr-old) ewes (8.0 and 6.1 kg, respectively).

Least-squares means for the season × NLW nested within NLB and age class effect were used to compare ewe BW among litter sizes within season and age class (Table 2). Yearling ewe BW in the spring or fall was not affected ($P \geq 0.20$) by litter size class. Adult ewes that gestated and weaned one lamb were heavier ($P \leq 0.01$) than all other litter size classes in the spring and all but one class in the fall (ewes that gestated 3+ lambs and weaned 1; $P > 0.99$). Within ewes that produced multiple lambs, a reduction in litter size at weaning by 1 lamb had no effect on ewe BW in spring or fall ($P \geq 0.91$). However, twin-bearing ewes were generally heavier than most triplet bearing classes. From this model, breed type differences in average BW across age class and age were reduced compared with those in Table 1, to 65.8, 65.9, and 62.6 kg for Rambouillet, Polypay, and RW-RA ewes, respectively, but the main effect of breed type remained significant ($P = 0.03$).

Wool Characteristics

Significant ewe birth year × age and ewe breed type × age interactions were detected in the analysis of GFW, CFW, AFD, SD-FD, CV-FD, CF, and CRV ($P \leq 0.02$). However, the main effects or interaction effects involving ewe birth year are not discussed because annual variation in performance is expected but difficult to attribute to specific environmental effects. Since the major focus of the present study was to compare the production of ewe breed types, comparisons of means among breed types were made within age (Table 3).

Greasy fleece weight within ewe age differed ($P \leq 0.05$) among breed types; 1- and 4-yr-old Rambouillet GFW were the heaviest, Polypay were intermediate, and RW-RA fleeces were the lightest. Average laboratory scoured yields were 58.9%, 63.1%, and 70.2% for Rambouillet, Polypay, and RW-RA, respectively. After adjusting GFW for average laboratory scoured yield, CFW of 1-yr-old ewes were not different ($P \geq 0.96$) among breed types. However, within 4-yr-old ewes, Rambouillet had the heaviest CFW ($P < 0.001$) and CFW of Polypay and RW-RA ewes were not different ($P > 0.99$).

Least squares means for AFD within ewe age differed among breed types ($P < 0.001$); 1- and 4-yr-old Rambouillet were finest, RW-RA were intermediate, and Polypay were coarsest. Within 1- and 4-yr-old ewes, variation in fiber diameter across the staple, measured as SD-FD, was lowest in Rambouillet, intermediate in Polypay, and greatest in RW-RA samples ($P < 0.001$). Within 1- and 4-yr-old ewes, CV-FD was greatest in RW-RA ($P < 0.001$), but no differences ($P > 0.99$) were detected between Rambouillet and Polypay.

Within 1-yr-old ewes, Rambouillet mid-side samples had the greatest CF ($P < 0.001$) compared with Polypay and RW-RA, which were not different

Table 2. Least squares means and greatest SE of BW for the season × number of lambs weaned (NLW) nested within number of lambs born (NLB) and age class effect of yearling and adult (2-, 3-, and 4-yr-old) ewes that weaned at least one lamb

Age class	NLB	NLW	n	Ewe BW, kg		
				Spring	Fall	Greatest SE
Yearling	1	1	235	50.8	60.0	0.63
	2	1	50	49.9	61.3	0.85
	2	2	55	48.9	59.8	0.82
Adult	1	1	321	66.9[a]	73.6[a]	0.61
	2	1	133	63.0[b]	71.8[b,c]	0.67
	2	2	702	62.7[b]	71.0[b,c]	0.58
	3+	1	32	63.8[b]	73.2[a,b]	0.92
	3+	2	98	60.5[c]	70.2[c]	0.71
	3+	3	46	60.9[b,c]	70.1[b,c]	0.84

[a–c]Means within a season and ewe age class with no superscript in common differ ($P \leq 0.04$) using the Tukey–Kramer mean separation procedure.

Table 3. Least squares means and greatest SE of wool characteristics for the ewe age × breed type interaction effect of Rambouillet (RA), Polypay (PP), and Romanov–White Dorper × Rambouillet (RW-RA) ewes

		Trait†						
Item*	*n*	GFW, kg	CFW, kg	AFD, µm	SD-FD, µm	CV-FD, %	CF, %	CRV, °/mm
1 × RA	208	2.45[a]	1.44	20.1[a]	4.23[c]	21.1[b]	98.6[a]	104.8[a]
1 × PP	231	2.22[b]	1.40	24.2[c]	5.17[b]	21.2[b]	88.7[b]	96.1[b]
1 × RW-RA	228	2.01[c]	1.40	22.8[b]	7.08[a]	30.9[a]	89.8[b]	87.7[c]
Greatest SE		0.06	0.04	0.20	0.13	0.54	0.79	1.64
4 × RA	123	3.91[a]	2.30[a]	21.9[a]	4.17[c]	19.0[b]	95.9[a]	109.5[a]
4 × PP	123	2.91[b]	1.83[b]	26.7[c]	5.21[b]	19.4[b]	76.1[c]	91.9[b]
4 × RW-RA	162	2.64[c]	1.86[b]	24.8[b]	6.56[a]	26.4[a]	83.5[b]	87.1[b]
Greatest SE		0.07	0.04	0.22	0.15	0.59	0.83	1.73

*Ewe age (in years) listed first, ewe breed type second.

†GFW, greasy fleece weight; CFW, clean fleece weight estimated from within breed type and ewe age composited laboratory scoured yield (RA = 58.9%; PP = 63.1%; RW-RA = 70.2%); AFD, average fiber diameter; SD-FD, SD of fiber diameter; CV-FD, CV of fiber diameter; CF, comfort factor (percentage of fibers < 30 µm in diameter); CRV, fiber curvature (i.e., crimp pattern).

[a–c]Means within a column and ewe age with no superscript in common differ ($P \le 0.05$) using the Tukey–Kramer mean separation procedure.

(P = 0.90). The CF of all breed types differed (P < 0.001) in 4-yr-old ewes; Rambouillet was the greatest, RW-RA were intermediate, and Polypay mid-side wool samples were the least. Within 1-yr-old ewes, all breed types differed (P < 0.01) in CRV; Rambouillet had the greatest, Polypay intermediate, and RW-RA the least. Within 4-yr-old ewes, Rambouillet also had the greatest CRV (P < 0.01), but CRV of Polypay and RW-RA were not different (P = 0.34).

The interaction effect of ewe birth year × breed type was only detected in the analysis of %M, %K, and %T ($P \le 0.03$). The cause of this interaction was due to larger differences in medullated fiber content among ewe breed types born in 2009 compared with other birth years. Nevertheless, there was no re-ranking among ewe breed types across birth years. The main effect of ewe breed type on %M, %K, and %T was highly significant (P < 0.001;Table 4). Mid-side wool samples from RW-RA had greater %M and %K (P < 0.001) than Rambouillet and Polypay, which were not different (P > 0.99). It follows that %T was also greater in RW-RA (P < 0.001) than Rambouillet and Polypay, which were not different (P > 0.99).

DISCUSSION

Ewe BW

The assessment of differences in ewe BW and interpretation of its effect on productivity and profitability are not always straightforward. Measurements of BW reflect genetic differences in adult body size and maturation rate but also are both affected by, and potentially have corresponding future effects on, reproductive performance and ewe productivity. Genetic differences for adult size among breeds, when adjusted to comparable levels of physiological maturity and body fat reserves, are expected to be positively associated with progeny differences in postweaning growth potential, harvest weights at comparable levels of fatness, and efficiency of postweaning gains to such an endpoint. However, more prolific ewes are expected to produce more twin and triplet litters, and these lambs are expected to be lighter at weaning and take more time after weaning to reach weight- or fat-constant harvest endpoints. Likewise, ewe lambs out of more prolific dams may potentially have poorer lambing rates and smaller litters as yearlings compared with heavier ewe lambs from smaller litters. More prolific ewes are also expected to lose more BW during lactation and weigh less at breeding than less

Table 4. Least squares means (±SE) for percentage med (%M), kemp (%K), and total medullated fiber (%M + %K; %T) of Rambouillet (RA), Polypay (PP), and Romanov–White Dorper × Rambouillet (RW-RA) ewes

		Trait		
Breed type	*n*	%M	%K	%T
RA	44	0.20 ± 0.15[b]	0.010 ± 0.046[b]	0.21 ± 0.19[b]
PP	44	0.19 ± 0.15[b]	0.011 ± 0.047[b]	0.20 ± 0.19[b]
RW-RA	40	1.13 ± 0.16[a]	0.313 ± 0.049[a]	1.44 ± 0.20[a]

[a,b]Means within a column with no superscript in common differ ($P < 0.001$) using the Tukey–Kramer mean separation procedure.

prolific ewes, potentially resulting in lower subsequent lambing rates and reduced longevity (Notter et al., 2018).

Notter et al. (2017) reported that Polypay and RW-RA ewes had higher fertility and more lambs born and weaned than did Rambouillet ewes, but exhibited no apparent negative carryover effects of greater early fecundity on subsequent productivity or longevity through 4 yr of age. The earlier maturity of the Polypay and RW-RA, augmented by effects of heterosis in these semi-prolific crossbred types, therefore more than compensated for the somewhat greater BW and lamb growth potential of the Rambouillet. In the present study, Rambouillet and Polypay ewes were similar in BW, and nearly identical when BW was adjusted for differences in reproductive performance, suggesting the similar potential for postweaning growth in the progeny of these two ewe types. The average BW of RW-RA ewes was 3.8 kg less than that of Rambouillet and Polypay ewes, but approximately 17% of this difference was attributed to differences in reproductive performance and would not be expected to be reflected in differences in postweaning performance of their offspring.

The ratio of total weight of lamb weaned to ewe BW or metabolic BW ($BW^{0.75}$) has been evaluated as an indicator of ewe production efficiency (Vatankhah and Salehi, 2010; Annett et al., 2011; Lôbo et al., 2012). Estimates of annual litter weaning weight for adult (2- through 4-yr-old) Rambouillet, Polypay, and RW-RA ewes when bred to terminal sires were 47, 54, and 56 kg per ewe, respectively (Notter et al., 2017). When annual litter weaning weight was expressed as a percentage of average ewe BW across season in the present study (Table 1), Rambouillet, Polypay, and RW-RA ewes averaged 71%, 83%, and 90%, respectively. As a percentage of ewe $BW^{0.75}$, ewe production efficiency was 203%, 235%, and 253% for Rambouillet, Polypay, and RW-RA ewes, respectively. Though these metrics are a useful indicator of ewe production efficiency, it does not account for the greater relative nutrient requirements for gestation and lactation in more prolific ewes.

Wool Characteristics

As expected, Rambouillet ewes produced the highest quality fleeces in the present study. Past research has investigated the effect of Romanov or hair sheep breeding on fleece traits of F_1 progeny. However, neither the independent nor combinatorial effect of ¼ Romanov and/or hair sheep breeding on wool quality has been previously reported. Although the design of the present study did not allow observed differences to be attributed to independent Romanov or White Dorper breed effects, fleeces from RW-RA ewes are marketable and pose limited risk of medullated fiber contamination.

Berger and Lupton (1994) evaluated fleece and fiber characteristics of Romanov × Targhee ewes raised in Wisconsin and reported average GFW and CFW of 3.08 and 2.00 kg, respectively. Similarly, Lupton et al. (2004) observed average GFW and CFW of 3.37 and 2.14 kg, respectively, for Romanov × Western white-faced ewes in Nebraska. However, reports investigating the direct effect of Romanov vs. fine- or medium-wool breeding on wool characteristics of crossbred sheep are not common. In Quebec, composite ewes (Dorset, Leicester, Suffolk) were bred to Romanov or Booroola Merino rams and resulting F_1 ewes recorded GFW of 2.92 and 3.47 kg, respectively (Fahmy, 1996). Because F_1 hair-breed-cross sheep produce a fleece that is reputed to be generally unmarketable, their wool characteristics have not been extensively evaluated. Bunge et al. (1996) quantified wool traits in F_1 ewes that were daughters of Suffolk or Targhee dams and wool (Booroola Merino, Combo-6, Finnsheep) or hair producing (Barbados, St. Croix) sire breeds and reared in Illinois. Ewes sired by hair breeds produced fleeces that were, on average, 1.73 kg lighter on a greasy basis but 8.12% higher yielding than those sired by wool breeds.

Average fiber diameter is the major pricing determinant of clean wool marketed domestically and internationally. Medullated fibers such as med (48–60 µm) and kemp (80–100 µm) generally have a larger diameter than wool fibers and will thus increase a fleece's AFD and SD-FD if present at a significant proportion. The Romanov produces a fleece consisting of coarse outer hair and a wool undercoat, whereas the coat of hair breeds has a high med fiber content. Mid-side wool samples of Romanov × Western white-faced ewes had AFD and SD-FD of 23.6–26.1 µm and 6.6–6.9 µm, respectively (Berger and Lupton, 1994; Lupton et al., 2004). Not surprisingly, Bunge et al. (1996) reported that AFD of ewes sired by hair breeds was 2.64 µm coarser than those sired by wool breeds.

Regardless of a fleece's weight, yield, or AFD, its medullated fiber content has important end-product quality implications. Such medullated fibers present challenges for manufacturers as they lack tensile strength, can easily break during first-stage processing, and resist dye, which can create color inconsistency in resulting fabrics (Morgan, 2003). Berger and Lupton (1994) reported that medullated fibers were detected in 95% of Romanov × Targhee ewe fleeces and, on average, contained 0.48% kemp and 0.75% med fibers. Similarly, Goot et al. (1979) reported that kemp-like fibers were present in 95% of Romanov × Mutton Merino ewe fleeces. As expected, mid-side wool samples of hair breed-cross F_1 ewes in Bunge et al. (1996) had 0.98% more kemp and 5.06% more med fibers than ewes sired by wool producing breeds.

Quantification of fiber medullation on a raw wool basis is rarely employed in standard core testing protocols in commercially traded, medium wools in the United States (W. C. Stewart, personal communication). From an Australian wool marketing perspective, Morgan (2003) mentioned that buyers acknowledge that non-Merino wools inherently pose medullated fiber risk but that a significant portion of these fibers will be removed during later stages of processing. Nevertheless, U.S. buyers generally mitigate objectionable fiber risk by inquiring about breed make-up of lots of wool and by relying on seller reputation. Stobart et al. (1986) observed that medullated fibers were relatively common in medium-wool breeds such as the Polypay with a reported range of 0.2–1.6% in processed wool with an AFD of 27.3 to 29.2 µm. However, there is no agreed upon medullated fiber level that results in reduced quality of wool products in international markets. In the United States, Berger and Lupton (1994) suggested a %K threshold of 0.5%. In the current study, 100% of the RA and PP fleeces contained less than 0.5% kemp fibers compared with 82.5% of the RW-RA fleeces. Therefore, the %K values for RW-RA sheep in the current study represent a slight contamination risk. This risk can be minimized if these ewes are shorn and bagged separately from wool with low medullated fiber content and buyers are informed of the genetic background of the ewes.

Comfort factor is the percentage of fibers less than 30 µm in diameter, which is a threshold above which a fiber will not bend and will be more likely to cause irritation when it comes in contact with human skin (Garnsworthy et al., 1988; Naylor, 1992). Therefore, CF is influenced by the mean and SD of a normally distributed fiber diameter sample (i.e., AFD and SD-FD). A CF greater than 95% indicates that the wool is suitable for close-to-skin garment applications that would be processed through the worsted system. Estimates of CF in the present study indicate that Rambouillet wool (97%) is well-suited to worsted applications, whereas Polypay (82%) and RW-RA (87%) would be more appropriate for woolen processing (Stobart et al., 1986).

Curvature is an indicator of crimp pattern along the staple and, while not a major pricing determinant for wool marketed in the United States, may impart desirable characteristics to yarn and end-products (McGregor and Postle, 2002, 2007). For example, McGregor et al. (2015) created next-to-skin fabrics made with 17 µm wool of high (114°/mm) and low curvature (74°/mm) and human subjects reported greater breathability and comfort with increased curvature. Therefore, the perceived comfort of woolen products may not be solely dependent on AFD and CF. However, since curvature and AFD are negatively phenotypically correlated with one another (−0.55; Pickering et al., 2013), wool graders may inadvertently visually identify fine wool based on its greater degree of crimp. This relationship does not seem to hold for RW-RA wool since it had acceptable AFD but low CRV, likely because of its greater %M and %K. Nevertheless, buyers wishing to visually identify RW-RA wool might be able to do so based on its reduced crimp.

The spinning count system (i.e., English grade) specifies an AFD range and a maximum permissible SD-FD for each corresponding grade (Table 5). As spinning count grade decreases (i.e., coarser AFD), the maximum SD-FD to qualify for that grade increases. Greater SD-FD of RW-RA fleeces resulted in a larger proportion being

Table 5. Spinning count system grades and corresponding average fiber diameter (AFD) range, maximum permissible standard deviation of fiber diameter (SD-FD), and percentages of fleeces in each class for 4-yr-old Rambouillet (RA), Polypay (PP), and Romanov–White Dorper × Rambouillet (RW-RA) ewes

				Percentage for:		
Grade	AFD range, µm	SD-FD limit, µm	Value,[1] $/kg	RA	PP	RW-RA
80s	17.70–19.14	4.09	10.77	3	0	0
70s	19.15–20.59	4.59	8.57	20	1	0
64s	20.60–22.04	5.19	8.17	33	0	5
62s	22.05–23.49	5.89	7.09	26	6	9
60s	23.50–24.94	6.49	6.72	12	13	23
58s	24.95–26.39	7.09	5.75	4	28	33
56s	26.40–27.84	7.59	5.04	2	19	18
54s–50s	27.85–30.99	8.19–8.69	4.01	0	33	12

[1]Value = average price received for clean wool by spinning count grade in territory states from 2007 to 2017 (USDA-AMS, 2007–2017).

disqualified from their corresponding AFD spinning count grade. On an individual-adult fleece (i.e., 4-yr-old) basis, 6 out of 123 (4.9%) Rambouillet, 1 out of 123 (0.8%) Polypay, and 74 out of 162 (45.7%) RW-RA samples would be downgraded because of their excessive SD-FD. After applying downgrades, the majority (59%) of Rambouillet fleeces would be graded as 64s or 62s. Although more RW-RA fleeces were downgraded, the majority (56%) would be in a spinning count grade of 60s or 58s whereas most (52%) Polypay fleeces would be graded at slightly coarser 56s or 54s grades.

A final important value determining characteristic of wool is color, as nonwhite fleeces are usually not suitable for commercial marketing. As a purebred, the Romanov produces a nonwhite fleece. However, fleeces of Romanov × white-faced fine-wool ewes are generally white (83%; Lupton et al., 2004) and the majority do not contain any pigmented fibers (79%; Goot et al., 1979). Fleece brightness or proportion of colored fibers was not quantified in the current study, but it is expected that RW-RA fleeces would pose a greater risk of nonwhite fibers than Rambouillet or Polypay fleeces.

Expected Annual Wool and Lamb Receipts

Average clean price by spinning count grade for territory wool (i.e., "western" or "range" states of the United States) from 2007 to 2017 are presented in Table 5 (USDA-AMS). With observed spinning count grade frequencies and average CFW of 4-yr-old ewes from the present study, expected annual wool receipts were $17.66, $9.65, and $10.93 per mature Rambouillet, Polypay, and RW-RA ewe, respectively. Based on an average price of $3.48/kg for 27–41 kg feeder lambs marketed in the states of TX, CO, and SD in this time period (USDA-AMS) and estimates of total litter weaning weight per ewe lambing (Notter et al., 2017), expected annual lamb receipts per mature Rambouillet, Polypay, and RW-RA ewe were $164, $188, and $195, respectively. Therefore, gross total revenue per mature ewe was expected to be similar for Polypay ($198) and RW-RA ewes ($206) and least for Rambouillet ewes ($182).

Implications

Few reports have directly compared production characteristics of crossbred sheep consisting of Western white-faced, highly prolific, and hair breeds. Results from this study indicated superiority for wool production and most desirable wool quality characteristics for fleeces from Rambouillet ewes compared with coarser, more variable fleeces from Polypay and RW-RA ewes. However, greater lamb production observed in Polypay and RW-RA ewes was associated with greater gross total revenue for these breed types. Thus, selection decisions and crossbreeding systems in Western rangeland sheep enterprises should continue to prioritize the improvement of lamb production and ewe longevity with a secondary emphasis on fleece traits. Nevertheless, there is value in Rambouillet crossbred wool consisting of up to ¼ hair sheep or Romanov breeding, and these fleeces should not be discarded from commercial wool markets as is common for ½ hair sheep fleeces.

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