

Lamb performance in hardwood silvopastures, I: animal gains and forage measures in summer

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ABSTRACT: The integration of trees into pasture systems can have variable effects on forage and animal growth. Some reports of these systems have indicated that animal gains are similar or better even when tree presence lowers forage yield. Forage production and animal performance were compared in black walnut (*Juglans nigra* L.)-based and honeylocust (*Gleditsia triacanthos* L.)-based silvopasture systems and open pastures in a randomized complete block design with three blocks over three summers. Cool season-based, mixed grass pastures were rotationally stocked with four to seven lambs depending on available forage. A rising plate meter was used to estimate pre- and post-graze forage mass. Forage samples of the mixed sward were collected and analyzed for nitrogen (N) and neutral detergent fiber (NDF) concentrations. Species percent cover was estimated using a modified Daubenmire approach at the same 12 points within each experimental unit every 4 wk during the study. Pre-graze herbage mass was similar ($P = 0.0717$) in honeylocust silvopastures

($5020 \pm 30 \text{ kg} \cdot \text{ha}^{-1}$) and open pastures ($4930 \pm 30 \text{ kg} \cdot \text{ha}^{-1}$) and lowest ($P < 0.0001$) in the black walnut silvopastures ($3560 \pm 30 \text{ kg} \cdot \text{ha}^{-1}$). Forages in the black walnut and honeylocust silvopastures had similar ($P = 0.4867$) N concentrations (23.3 ± 0.4 and $23.9 \pm 0.4 \text{ g} \cdot \text{kg}^{-1}$, respectively), which was greater ($P \leq 0.0003$) than that of the forages in the open pastures ($21.0 \pm 0.4 \text{ g} \cdot \text{kg}^{-1}$). Forages in the honeylocust silvopasture had lower ($P \leq 0.0042$) NDF concentrations ($507 \pm 3 \text{ g} \cdot \text{kg}^{-1}$) than forages in the black walnut silvopasture and open pastures (mean = $525 \pm 3 \text{ g} \cdot \text{kg}^{-1}$). Forage species present in the black walnut silvopastures differed from those present in the open and honeylocust systems, which had similar composition. Despite differences in stocking rates, total lamb weight gains per system did not differ ($P \geq 0.7592$) among black walnut, honeylocust, and open pasture systems (10 ± 2 , 12 ± 2 , and $10 \pm 2 \text{ kg} \cdot \text{d}^{-1}$, respectively). Silvopasture practices can improve land productivity when incorporated into cool season forage pastures.

Key words: black walnut, honeylocust, nutritive value, species composition

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INTRODUCTION

Silvopasture is a land-management practice in which trees are integrated with pasture-based livestock systems to provide both short- and long-term

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returns from the same land base (Sharrow et al., 2009). Livestock in silvopasture systems can benefit from shade in summer and shelter from wind and frozen precipitation in winter. The trees in turn may benefit from the managed livestock presence through increased nutrient inputs, amplified nutrient cycling, and suppression of weedy or invasive species. Along with production and environmental benefits, silvopasture systems may require fewer nutrient inputs because of nitrogen (N)-fixing trees or forages; increase and diversify marketable products; and produce aesthetically pleasing landscapes that add value to farms and rural economies.

Maintaining adequate livestock production in silvopastures will be of primary concern to most livestock producers considering silvopasture implementation. Although some have reported forage production declines in silvopastures (Kallenbach et al., 2006; Kyriazopoulos et al., 2013), this is in part a function of tree density (Burner and Brauer, 2003; Belesky, 2005; Buergler et al., 2005). Despite resource competition between forages and trees, reductions in forage quantity might be ameliorated by increased forage nutritive value, whether as a function of cooler temperatures under trees (Buergler et al., 2006) and delays in vernalization (Neel et al., 2016) or improved soil physical characteristics (Chander et al., 1998; Michel et al., 2007; Sharrow, 2007). However, lower soluble carbohydrates (Buergler et al., 2006) and only moderate, variable responses in fiber digestibility (Fannon et al., 2019) in silvopasture forages challenge this idea. Nevertheless, several studies have demonstrated no reduction in animal growth despite lower available forage (Lehmkuhler et al., 2003; Kallenbach et al., 2006; Fannon et al., 2019). The objective of this study was to determine forage response and lamb performance within hardwood silvopasture systems compared to open pastures.

MATERIALS AND METHODS

All procedures were approved by the Virginia Tech Institutional Animal Care and Use Committee under protocol number 14-075.

Research Site

This 3-yr, 12-wk grazing study was conducted in the summers of 2014 through 2016 at the Whitethorne Agroforestry Demonstration Center, located at Virginia Tech's Kentland Farm in Blacksburg, Virginia (37.20N 80.58W). Soil series on the site include Berks–Lowell–Rayne complex, Unison and Braddock soils, and Weaver soils,

arranged in order of decreasing slopes from 25% to 65%, 15% to 25%, and 0% to 5%, respectively. These soils are generally fine or fine-loamy mixed materials formed along river terraces.

Weather

Air temperature (AT; °C), relative humidity (RH; %), gross radiation ($\text{kW}\cdot\text{m}^{-2}$), and precipitation (0.25-mm increments) data were collected from a weather station located on Kentland Farm, about 500 m from the study site. The AT and RH data were used to calculate the Temperature Humidity Index (THI) following Mader et al. (2006):

$$\text{THI} = (0.8 \times \text{AT}) + \left[\left(\frac{\text{RH}}{100} \right) \times (\text{AT} - 14.4) \right] + 46.4$$

Historical weather data (1981 to 2010) for 30-yr averages were downloaded from <http://www.weather.gov/rnk/MonthlyClimateNormals> under Blacksburg, including average minimum and maximum temperatures and total precipitation by month.

Pasture and Tree Management

The silvopasture treatments had been established in what was a uniform, cool season pasture in 1995. Infection levels of tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumont., syn. *Lolium arundinaceum* (Schreb.) Darbysh., formerly *Festuca arundinacea* Schreb.) with an ergot alkaloid-producing endophyte (*Neotyphodium coenophialum* [Morgan-Jones and Gams] Glenn, Bacon, and Hanlin) were greater than 75% for all pastures. The trees were thinned to a final density in 2012, leaving an approximate $12.2 \times 12.2\text{-m}$ configuration, with about $36 \text{ stems}\cdot\text{ha}^{-1}$. Open and silvopasture treatments were replicated three times across the site in a randomized complete block design (Fig. 1). The total area of each experimental unit (EU) was $0.27 \text{ ha}\cdot\text{EU}^{-1}$, and each EU was subdivided into eight paddocks for rotational stocking.

Cattle (*Bos taurus*) grazed the site once in the spring of each year prior to the grazing study. Following spring grazing with cattle, pastures were clipped with a rotary mower to remove seedheads (15 to 20 cm). Sheep (*Ovis aries*) also grazed the site for 6 wk as part of a second study during fall 2015.

N was applied as urea in May 2014 and 2015 at a rate of $67 \text{ kg}\cdot\text{ha}^{-1}$. Pastures also were fertilized for a stockpiling study in fall 2015, thus no fertility was added in spring 2016. Red and white clover (*Trifolium pratense* L. and *Trifolium repens* L.) seed were broadcast in all EUs at a rate



Figure 1. Aerial view of study site with three replicates of two silvopasture systems (black walnut and honeylocust) and an open pasture system.

of 4 and 1 kg·ha⁻¹, respectively, in the winter of 2013, and red clover was broadcast in all EUs at 4 kg·ha⁻¹ in the beginning of 2016. Owing to undesirable species and associated low productivity in the black walnut (*Juglans nigra* L.) silvopastures, 4.8 kg·ha⁻¹ of tall fescue (cv. Kentucky 31) seed and 1.1 kg·ha⁻¹ of orchardgrass (*Dactylis glomerata* L. cv. Benchmark+) seed were broadcast over each black walnut silvopasture EU after the second summer, followed by two passes with a drag harrow.

To control yellow crownbeard (*Verbesina occidentalis* (L.) Walter), all EUs in block one, and all of the black walnut and half (four) of the honeylocust (*Gleditsia triacanthos* L.) silvopasture paddocks in block two were treated with GlyStar Plus (Albaugh, LLC, Ankeny, IA). The herbicide was spot applied in a 2:1 ratio (water:herbicide) using a Rotowiper (Rotowiper Ltd, Ashburton, New Zealand) to minimize damage to the forage stand. To improve stickweed control, pastures were retreated after sheep were removed from the site in year 2 (2015). This time, all pastures were clipped to 13 cm and 10 d later all black walnut silvopasture systems and the open system in block one were treated with 5 L·ha⁻¹ of Weedar 64 2,4-D amine broadleaf herbicide (Nufarm Ltd, Laverton, Australia) using a boom sprayer. At this time, any large spots of stickweed throughout all other EUs were spot sprayed with the same herbicide mixture using a backpack sprayer. Early in summer 2016, all paddocks were spot sprayed with 23 mL·L⁻¹ Weedar 64 2,4-D amine broadleaf herbicide (Nufarm Ltd) using a backpack sprayer, targeting stickweed, Canada thistle (*Cirsium arvense* (L.) Scop.), milk thistle (*Silybum marianum* (L.) Gaertn.), blackberry (*Rubus* spp.), autumn olive (*Elaeagnus umbellata* Thunb.), and any honeylocust sprouts in non-honeylocust silvopasture treatments.

Tree management over the three seasons was largely limited to the winter prior to the 2016 grazing season. Trees in silvopastures were trimmed to maintain clear boles from the ground to the first branch (2.5 to 5 m height). Stump growth (from

trees thinned in 2008 and 2012) was trimmed to 54 to 60 cm height.

Sheep

In 2014, Suffolk and Dorset crossbred ewe lambs ($n = 28$) and wethers ($n = 22$) were acquired from a farm in Pulaski County, VA. They received a booster vaccination for *Clostridium perfringens* and a dose of deworming medication (May 9, 2014). Lambs were maintained as a single group on open (nontreatment) pastures adjacent to the research site until study initiation (June 18, 2014).

In 2015, Suffolk and Dorset crossbred ewe lambs ($n = 60$) and ram lambs ($n = 10$) were acquired from a farm in Pulaski County, VA. Ram lambs were banded and all sheep were dosed with 8.8 mg·kg⁻¹ body weight (BW) of Prohibit Levamisole Drench solution (AgriLabs, St. Joseph, MO) and given a booster vaccination for *Clostridium perfringens* (May 22, 2015). Lambs grazed the adjacent pasture for 8 d before study initiation (May 30, 2015). At 8 wk (July 23, 2015), the lambs' level of anemia was scored based on the color of their lower eyelids according to the FAMACHA protocol as described by Kaplan et al. (2004). Any lamb with a score of three or greater received 8.8 mg·kg⁻¹ BW of Prohibit Levamisole Drench solution (AgriLabs). The same deworming protocol was followed at weeks 10 and 12.

In 2016, Dorper and Dorset crossbred ewe lambs ($n = 49$) and wethers ($n = 21$) were acquired from a farm in Scott County, VA. All sheep were dosed with 8.8 mg·kg⁻¹ BW of Prohibit Levamisole Drench solution, 0.2 mg·kg⁻¹ BW of Cydectin Oral Sheep Drench (Boehringer Ingelheim, Vetmedica, Inc, St. Joseph, MO), and 4.5 mg·kg⁻¹ BW of Panacur Sheep Drench (Intervet Inc/Merck Animal Health, Madison, NJ). Lambs received a booster vaccination for *Clostridium perfringens* at the initiation of the study (May 19, 2016). At the second week (June 2, 2016), the lambs' anemia levels were scored and treatments administered as described, and the same deworming protocol was followed every 2 wk thereafter.

Southern States Sheep Mineral with Zinpro (Southern States Cooperative, Inc, Richmond, VA) and water were provided ad libitum to all lambs throughout the duration of the study.

Stocking Rates and Methods

Each year, lambs were stratified by sex and BW. In the third year, lambs were also stratified by predominant body color (white, black, and tan). Lambs were then randomly assigned to each of the nine EUs.

Stocking rates for each treatment within years were set based on relative available herbage in each treatment estimated prior to study initiation each year. Stocking rates (defined by animal weight rather than number) were reduced slightly each year to increase forage available to each lamb in an attempt to improve animal performance. Average lamb weights at the beginning of the study in 2014, 2015, and 2016 were 49, 25, and 21 kg, respectively. In the first year, the black walnut silvopastures were stocked with three ewes and one wether, whereas the remaining two treatments were stocked with three ewes and two wethers. In the second year, the black walnut silvopastures were stocked with six ewes, whereas the remaining two treatments were stocked with an additional wether. In the third year, the black walnut silvopastures were stocked with four ewes and one wether, whereas the remaining two treatments were stocked with five ewes and two wethers.

Sheep in all EUs were moved simultaneously to a fresh paddock once average residual forage heights reached about 7 cm. At the start of each rotation, sheep were allowed access to the half of the paddock where water was available. After about a third of the expected time (about 1 to 2 d) needed to graze a complete paddock had elapsed, sheep were provided access to the remaining (ungrazed) portion of the paddock. This practice was applied to improve evenness of forage utilization. Although this allowed the sheep to back-graze, this was necessary to provide access to water. Back-grazing generally lasted 2 to 4 d and had little effect on forage production based on visual observation.

Forage Mass

Forage mass and residue were estimated by taking 30 random measurements within each of the nine paddocks with a rising plate meter (Jenquip, Fielding, New Zealand) before and after each

rotation. Estimates of pre- and post-graze forage mass were calibrated to sward height. Calibrations were made by collecting three separate samples from under the rising plate within each EU at alternate measurement events. Following placement of the plate meter and recording of the plate height, the area of the plate was marked with a round quadrat and the plate meter was removed from the sward. Herbage samples within the quadrat were cut to ground level. Samples were dried in a forced air oven at approximately 55 °C for no less than 4 d, then weighed for dried forage mass. Masses of the clipped samples within each double-sampling event were regressed against forage height. Average plate meter heights from each measurement event were fitted to the regression equation to calculate total available forage on entry and residue on exit.

Forage Nutritive Value

At every other rotation, mixed grass samples were collected between 1200 and 1400 hours from each paddock to be stocked before entry by lambs. Species and their proportions in the grab sample were selected to approximate the relative proportion in which they were consumed by the lambs within the EU. Samples were cut at a 5 to 8 cm residual height and collected randomly from approximately 20 locations within the paddock. During the second and third years, an additional forage sample containing only orchardgrass also was collected.

Samples were dried in a forced air oven at approximately 55 °C for at least 4 d. Dried samples were ground in a Wiley Mill (Thomas Scientific, Swedesboro, NJ) with a 2-mm screen followed by a Cyclotec Sample Mill (FOSS North America, Eden Prairie, MN) with a 1-mm screen. All samples were scanned with a FOSS 6500 Composite NIR Spectrometer (FOSS North America) using ISIScan software (FOSS North America). Using WinISI software (FOSS North America), samples from the first 2 yr were grouped by similarity and representative samples were selected for further analysis of neutral detergent fiber (NDF) and N using wet chemistry techniques. NDF concentration was determined using an ANKOM 200 Fiber analyzer (ANKOM Technology, Macedon, NY) as described by Vogel et al. (1999). All samples were run in duplicate. Samples were considered for reanalysis if the coefficient of variation exceeded 4%. Total N was estimated using a Vario MAX CNS elemental analyzer (Elementar, Langensfeld, Germany). Single samples were run for analysis of N.

Forage Species Composition

Twelve randomly distributed points within each EU were selected to evaluate forage species composition. A modified Daubenmire approach (Daubenmire, 1959) was used to rank each species present within a 0.5- × 1.0-m quadrat in six cover classes. These classes included 1 (0% to 2.5%), 2 (2.6% to 25%), 3 (26% to 50%), 4 (51% to 75%), 5 (76% to 97.5%), and 6 (97.6% to 100%). Sample documentation at all 108 points occurred once at study initiation and again every fourth week until conclusion of the study each year.

The sum of each class for each species was calculated for each EU. This summation was multiplied by the midpoint of each class and the product for each class was summed for the estimate of total canopy cover by species. This was divided by the total number of sampled quadrats ($n = 12$) to estimate the percent canopy cover by species. The percent canopy cover of each species was divided by the total canopy cover of all species to estimate the species composition within each EU.

Lamb Performance

Throughout the first and second years, sick or deceased lambs were removed and replaced with lambs of similar size and sex, if possible. No replacements were necessary in the final year. Data for sick or deceased animals were removed from the BW analyses and data for replacement sheep were included in BW analyses for subsequent periods. A livestock crate was used to confine lambs during weighing on Tru-Test load cells (Tru-Test, Ltd, Auckland, New Zealand). Average BW was calculated from two un-shrunk BW measurements collected once per day for two consecutive days at days -1 and 0; 27 and 28; 55 and 56; and 83 and 84. Each of these three, 4-wk intervals was considered a single period.

Average daily gain (ADG) was calculated by dividing the average BW gain per period by 28 d. System gain was calculated by averaging the within-period BW gains of all healthy lambs in an EU and multiplying this by the total number of lambs in the EU. This approach was taken to correct for sick or deceased animals.

Statistical Analysis

The rising plate meter regression was calculated using a quadratic function of sward height against forage mass of the double samples with PROC

REG in SAS Studio, v. 3.5 (SAS Institute, Cary, NC). Regression equations were separated by treatment and included pre- and post-graze measures in a single equation. All Cook's outliers calculated in the first iteration of the program were removed from the analysis.

A mixed analysis of variance of ADG and system gain, pre- and post-graze forage herbage mass, forage N and NDF content, and species composition by species between treatments was analyzed with PROC MIXED in SAS Studio, v. 3.5 (SAS Institute). The study was conducted as a randomized complete block design with three replications. Year was included as a fixed effect. Repeated measures analysis by period was used with a compound symmetry covariance structure for the analysis of ADG. Repeated measures by sampling date were used with a standard variance covariance structure for the analysis of species cover, pre- and post-graze forage mass, and nutritive value of mixed grass and orchardgrass samples. LS means and Tukey's-adjusted differences were calculated. Differences were considered significant when $P < 0.05$.

For the analysis of species composition differences in percent cover, all warm season (C4) grasses were included in a category for analysis, as were all *Bromus* species. Broadleaf weeds included all broadleaf plants present except for clovers (red, white, or hop [*Trifolium campestre* Schreb.]) and honeylocust suckers or seedlings. Horse nettle (*Solanum carolinense* L.) was included in the broadleaf weed category, but was also analyzed separately.

RESULTS

Weather

Temperatures during the summer of 2014 were similar to or cooler than the historical average. The summers of 2015 and 2016 had hotter average minimum and maximum temperatures than the historical average (Table 1). Rainfall was lower during the study period compared to historical monthly totals, except for August and September 2014, and the final month of 2016. The beginning of each year was substantially dryer than the historical average.

July generally had the largest THI values (Fig. 2). Throughout most of each summer, conditions were within "uncomfortable" (70.0 to 74.9) and "stressful" (75.0 to 79.9) bounds (as defined by Silanikove, 2000). The THI exceeded the threshold (80.0) of "severe" heat stress twice in July 2014, once in June 2015 and five times in July 2015, and

Table 1. Average monthly minimum (min, °C) and maximum (max, °C) temperatures and total monthly precipitation (precip, cm) for each month of the study within years and 30-yr averages (1981 to 2010) at Kentland Farm, Blacksburg, VA

Month	Year									30-yr average		
	2014			2015			2016					
	Min	Max	Precip	Min	Max	Precip	Min	Max	Precip	Min	Max	Precip
	May	—	—	—	10.7	25.6	48.0	10.8	22.0	100.3	8.4	21.9
June	15.1	28.1	36.6	16.4	28.4	78.2	14.6	27.7	88.1	13.6	26.1	101.6
July	15.4	27.9	72.6	17.2	29.2	62.2	17.9	30.1	104.6	15.6	27.9	108.2
Aug	15.7	25.9	148.3	15.8	28.2	77.5	18.5	29.0	97.5	14.8	27.4	91.2
Sept	14.0	23.9	98.0	—	—	—	—	—	—	10.6	24.1	78.7

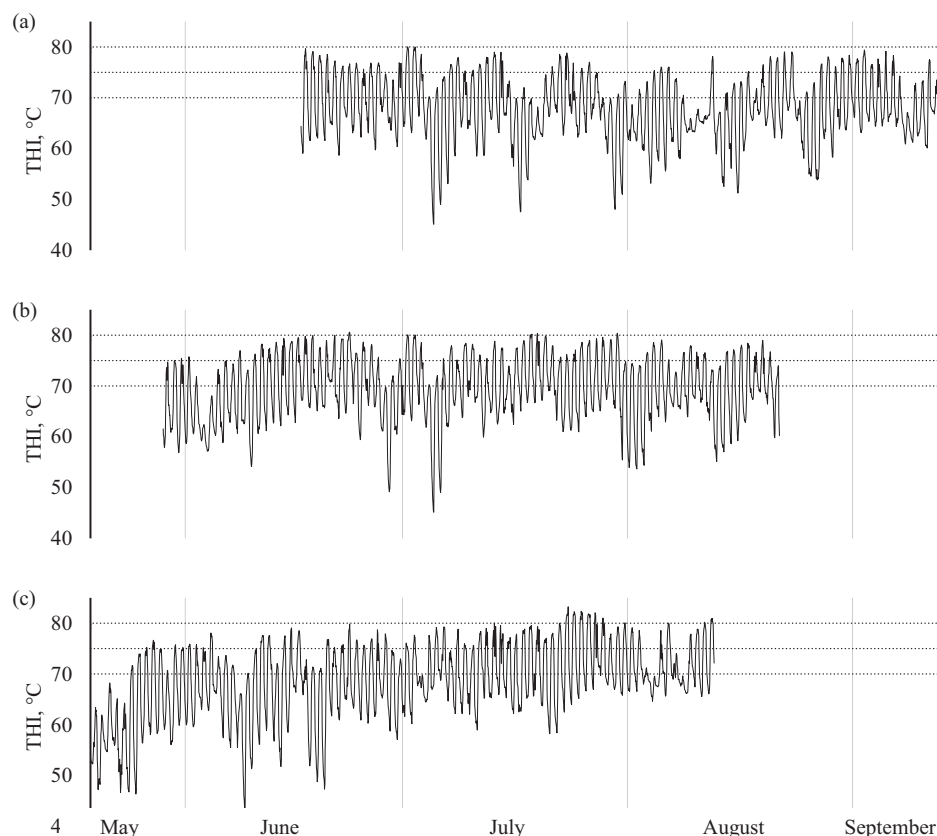


Figure 2. THI values during the study with thresholds (dotted lines) of uncomfortable (70 °C), stressful (75 °C), and severe (80 °C) zones of heat stress as defined by Silanikove (2000) during the study in 2014 (a), 2015 (b), and 2016 (c).

eight times in July 2016 and three times in August 2016. In 2014, the mean THI was 70.0, 67.9, 66.8, and 68.8 for June, July, August, and September, respectively. In 2015, the mean THI was 66.6, 69.0, 70.4, and 69.1 for May, June, July, and August, respectively. In 2016, the mean THI was 62.1, 67.2, 71.5, and 71.5 for May, June, July, and August, respectively.

On average, 2015 had sunnier days than the other 2 yr (Fig. 3). Solar radiation was similar in 2014 and 2016.

Spring was dry for all 3 yr compared to the historical averages, and this was particularly the

case in 2014 (Fig. 4). Despite a dry May in 2015 and 2016, precipitation generally was adequate for forage production during the latter 3 mo of the study in those years.

Forage Mass

The rising plate meter regression equations (Table 2) had the best fit in the honeylocust silvopastures followed by the regression equation in the black walnut silvopasture, and finally the open pasture. The regression for the black walnut silvopasture had a steeper slope and a lower intercept

compared to the open pasture and honeylocust silvopasture, respectively.

In the third year, pre-graze forage mass (Table 3) was greater in the honeylocust silvopastures than in the open pastures, but differences were not observed the previous 2 yr (year \times treatment interaction; $P = 0.0002$). Throughout all 3 yr, the black walnut silvopastures had about 70% to 72% of the pre-graze forage mass as the honeylocust silvopastures and open pastures, respectively.

Although the stocking rate of the three systems was adjusted to keep post-graze residue herbage mass roughly equivalent across systems, the black walnut silvopastures consistently had a lesser amount of estimated residue mass than the other systems for all 3 yr. Variations in the degree of difference over years led to significant ($P = 0.0070$) treatment \times year interaction.

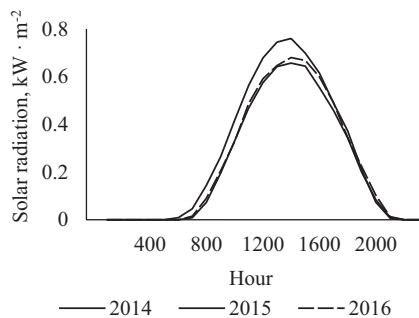


Figure 3. Mean solar radiation by year over a 24-h period.

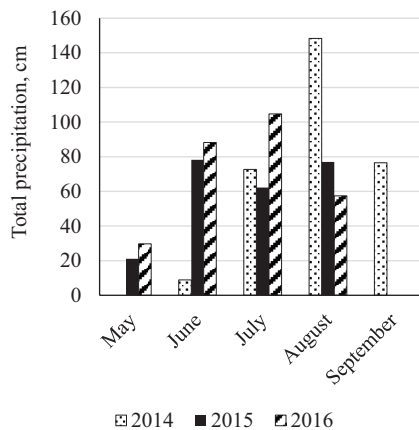


Figure 4. Monthly precipitation each year during the study.

Forage Nutritive value

For the mixed grass and orchardgrass-only samples, R^2 for the Near-Infrared Spectroscopy (NIRS) prediction model for N was 0.9682 and 0.9689, respectively. Forage N within the mixed grass samples was adequate (National Research Council, 2007) for lamb growth for all 3 yr in the silvopastures, but decreased over time (Table 4). On the basis of mixed grass samples, forage N was limiting for lamb growth in the open pastures in the second and third years and lowest in the open pasture for all 3 yr.

Forage N within the orchardgrass samples also was adequate (National Research Council, 2007) for lamb growth for both years it was sampled (Table 5). Orchardgrass in the black walnut silvopastures had greater levels of N than when grown in the open pastures. Orchardgrass N levels were similar in the honeylocust silvopastures and the open pastures.

For the mixed grass and orchardgrass-only samples, R^2 for the NIRS prediction model for NDF was 0.8702 and 0.9402, respectively. Forage NDF from mixed samples varied by treatment and year (treatment \times year interaction; $P = 0.0089$). Mixed forages within the honeylocust silvopastures had lower NDF concentrations than forages in the black walnut silvopastures in the first 2 yr and lower NDF concentrations than forages in the open pastures in the first year. For orchardgrass-only samples, no difference in NDF concentrations was observed among treatments for both years.

Forage Species Composition

Changes in percent cover over years resulted in treatment \times year interaction for tall fescue ($P = 0.0063$), red clover ($P < 0.0001$), white clover ($P = 0.0210$), the broadleaf weeds ($P = 0.0037$), the warm season grasses ($P = 0.0256$), horse nettle ($P = 0.0398$), and *Bromus* spp. ($P = 0.0197$).

Warm season grasses, brome grasses, and broadleaf weeds were combined into respective categories for the analysis (Table 6). In addition to the identified species, 14 unidentified broadleaf plants were included in the analysis of broadleaf weeds.

Table 2. Rising plate meter regression equations and indicators of fit by treatment

Treatment ¹	Intercept	SE	Height (cm)	SE	Height ² (cm ²)	SE	R^2	Adjusted R^2
BW	5.09	1.29	0.742	0.134	-0.0075	0.0030	0.335	0.331
HL	11.06	1.49	0.597	0.125	-0.0042	0.0023	0.351	0.347
OP	8.22	1.64	0.877	0.142	-0.0111	0.0027	0.265	0.261

¹Treatment: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

Table 3. Forage mass and residue by treatment across three summers

Year	Treatment ¹			SE	Tukey's-adjusted <i>P</i> -values ¹		
	BW	HL	OP		BW vs. HL	BW vs. OP	HL vs. OP
Pre-graze, kg·ha ⁻¹							
2014	3560	4860	4910	50	<0.0001	<0.0001	0.9996
2015	3560	4910	4890	50	<0.0001	<0.0001	1.0000
2016	3560	5290	4990	50	<0.0001	<0.0001	0.0014
Average ²	3560	5020	4930	30	<0.0001	<0.0001	0.0717
Post-graze, kg·ha ⁻¹							
2014	2440	3560	3610	50	<0.0001	<0.0001	0.9978
2015	2540	3720	3880	50	<0.0001	<0.0001	0.2563
2016	2630	4020	3900	50	<0.0001	<0.0001	0.6744
Average ²	2540	3770	3796	30	<0.0001	<0.0001	0.6960

¹Treatment: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

²Presented by year and by all years combined despite treatment × year interaction in statistical model.

Table 4. Nutritive value characteristics of mixed forage samples collected across all three summers

Year	Treatment ¹			SE	Tukey's-adjusted <i>P</i> -values ¹		
	BW	HL	OP		BW vs. HL	BW vs. OP	HL vs. OP
N, g·kg ⁻¹							
2014	24.4	25.2	23.1	0.6	0.9969	0.8876	0.3989
2015	22.8	24.6	21.1	0.7	0.7162	0.7477	0.0200
2016	22.5	22.0	18.7	0.7	0.9998	0.0100	0.0533
Average ²	23.3	23.9	21.0	0.4	0.4867	0.0003	<0.0001
NDF, g·kg ⁻¹							
2014	505	474	500	5	0.0024	0.9987	0.0274
2015	543	509	521	6	0.0038	0.1945	0.9217
2016	534	536	546	6	1.0000	0.9224	0.9729
Average ²	528	507	522	3	<0.0001	0.4926	0.0042

¹Treatment: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

² N and NDF presented by year and by all years combined because of no treatment × year interaction in statistical model.

The percent cover of tall fescue (Table 7) fluctuated across the 3 yr in each treatment, but was consistently lowest in the black walnut silvopastures. No differences in percent tall fescue cover were observed between the other two systems. Percent cover of both red and white clover decreased over time, with the greatest loss occurring in the honeylocust silvopasture. Percent cover of broadleaf weeds also fluctuated over time in each treatment following attempts at broadleaf control in the various systems. Percent cover of horse nettle substantially increased in the last 2 yr from the first year in both the honeylocust silvopasture and the open pasture. The warm season grasses and *Bromus* spp. fluctuated across years within systems.

Lamb Performance

In 2014 and 2015, ADG did not differ ($P \geq 0.4632$) among systems (Table 8), but in 2016, ADG was greater ($P \leq 0.01$) for lambs in black

walnut silvopastures (treatment × year interaction; $P < 0.001$). ADG for lambs in honeylocust and open system did not differ in 2016. Total gain per system increased each consecutive year ($P < 0.001$), but there were no differences among treatments and no treatment × year interaction for total system output ($P = 0.8739$).

DISCUSSION

Forage Mass

The honeylocust silvopastures produced greater forage mass than the open pasture in the final year. Other studies have also shown a benefit to forage production in light shade (Buerger et al., 2005; Belesky et al., 2006). However, with these more mature (~20-yr-old) systems, forage mass on offer under black walnut trees was reduced by 28% compared to forage mass on offer in the open pastures. Similar findings were reported by Kallenbach et al. (2006) who measured 20% less ryegrass forage in

Table 5. Nutritive value characteristics of orchardgrass samples collected across second and third summers

Year	Treatment ¹			SE	Tukey's-adjusted <i>P</i> -values ¹		
	BW	HL	OP		BW vs. HL	BW vs. OP	HL vs. OP
	N, g·kg ⁻¹						
2015	24.5	24.5	22.3	0.7	1.0000	0.2942	0.2928
2016	24.4	22.7	21.8	0.7	0.5145	0.1087	0.9554
Average ²	24.5	23.6	22.1	0.5	0.4427	0.0035	0.0956
	NDF, g·kg ⁻¹						
2015	545	539	547	6	0.9846	1.0000	0.9522
2016	533	542	540	6	0.8736	0.9448	0.9999
Average ²	539	541	543	4	0.9472	0.7159	0.8870

¹Treatment: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

²N and NDF presented by year and by all years combined because of no treatment × year interaction in statistical model.

a pine and black walnut silvopasture compared to an open pasture. Burner (2003) also found less cool season forage production in pine silvopasture alleys than in open pastures.

Despite attempts to manage for equivalent residue forage mass across treatments, the black walnut silvopastures consistently had lower post-graze measures than the other systems. However, the post-graze estimates may have been underestimated in the black walnut silvopasture due to the steeper slope and lower intercept of the regression equation of sward height to forage mass for the black walnut silvopasture compared to the other systems, which were more similar to each other. This may have been a result of the less mature and thereby less rigid pre-graze sward of the black walnut silvopasture, which would reduce estimates of forage mass predictions for the post-graze sward. Lower residual forage in these systems at the end of each season apparently did not affect forage productivity in the subsequent years. Available forage mass in the honeylocust silvopastures increased each year, whereas the forage mass in the open pasture was variable over years, decreasing in 2015, and increasing in 2016.

Forage Nutritive Value

Forage N levels in the mixed grass samples steadily decreased in all treatments over each summer, although at different rates among treatments. This coincided with decreased clover in all systems, which likely led to lower N in the mixed forage samples. Orchardgrass N concentrations also decreased from the second to third years (the only years in which they were tested). However, it is unclear whether this is a consequence of less N fixation in the systems due to declining clover populations or attributable to the change in fertility application schedule.

Forage crude protein (CP) was adequate for lamb growth in the silvopastures (National Research Council, 2007), but inadequate for lamb growth in the open pastures in the second and third year. Given the greater levels of CP available in clovers and orchardgrass, the lambs may have been able to meet their CP requirements through selective grazing. If this were the case, there would be no noticeable effect of increased CP in the silvopasture forages on lamb weight gains in the different systems. Orchardgrass CP was adequate for lamb growth for all treatments.

Shade appears to directly affect N concentrations in these forages, independent of changes in botanical composition, although this is not always observed. An increase in silvopasture forage CP concentration was reported by Kallenbach et al. (2006) in Missouri, although not by Fannon et al. (2019) in Virginia. Orchardgrass plants in West Virginia had increasing CP content with increasing levels of shade along a woodland light gradient, and the ratios of total digestible nutrient (TDN) to CP indicated that N content was disproportionately high in potential silvopastoral conditions (Belesky et al., 2006). In a study of the effect of shade on various forage species, CP was generally elevated in forage grasses as shade levels increase (Lin et al., 2001).

NDF levels in the complete-sward pasture samples were lower in the honeylocust silvopastures than the open pasture in the first year, whereas in the test of orchardgrass samples alone, NDF levels did not differ across all treatments for both years. This suggests that the difference in NDF was driven by species composition in the mixed pasture sample and could perhaps be a function of greater clover populations in the honeylocust silvopastures in the first year. NDF levels in the black walnut silvopasture were likely inflated by the greater percent cover of warm season grasses in

Table 6. Herbaceous species present in pastures grouped into categories for species composition analysis

Category	Common name	Scientific name
Warm season grasses	Nimblewill	<i>Muhlenbergia schreberi</i>
	Johnsongrass	<i>Sorghum halepense</i>
	Yellow foxtail	<i>Setaria glauca</i>
	Crabgrass	<i>Digitaria</i> spp.
	Goosegrass	<i>Eleusine indica</i>
Brome grasses	Purpletop	<i>Tridens flavus</i>
	Soft chess	<i>Bromus mollis</i>
	Downy brome	<i>Bromus tectorum</i>
	Smooth brome	<i>Bromus inermis</i>
Broadleaf weeds	Stickweed	<i>Verbesina occidentalis</i>
	Wild basil	<i>Clinopodium vulgare</i>
	Horse nettle	<i>Solanum carolinense</i>
	Milk thistle	<i>Silybum marianum</i>
	Canada thistle	<i>Cirsium arvense</i>
	White campion	<i>Silene latifolia</i>
	Lambs quarters	<i>Chenopodium album</i>
	Fleabane	<i>Erigeron</i> spp.
	Yellow woodsorrel	<i>Oxalis stricta</i>
	Wood geranium	<i>Geranium maculatum</i>
	Dandelion	<i>Taraxacum</i> spp.
	Narrowleaf plantain	<i>Plantago lanceolata</i>
	Oxeye daisy	<i>Leucanthemum vulgare</i>
	Wild lettuce	<i>Lactuca virosa</i>
	Marestail	<i>Conyza canadensis</i>
	Common ragweed	<i>Ambrosia artemisiifolia</i>
	Blue violet	<i>Viola sororia</i>
	Henbit	<i>Lamium amplexicaule</i>
	Chickweed	<i>Stellaria media</i>
	Sulfur cinquefoil	<i>Potentilla recta</i>
	Japanese honeysuckle	<i>Lonicera japonica</i>
	Virginia pepperweed	<i>Lepidium virginicum</i>
	Curly dock	<i>Rumex crispus</i>
	Crown vetch	<i>Securigera varia</i>
	Blackberry	<i>Rubus</i> spp.
	Sow thistle	<i>Sonchus oleraceus</i>
	Pinnate tansy mustard	<i>Descurainia pinnata</i>
	Autumn olive	<i>Elaeagnus umbellata</i>
	Pink deptford	<i>Dianthus armeria</i>
	Poison ivy	<i>Toxicodendron radicans</i>
	Multiflora rose	<i>Rosa multiflora</i>
	Greater burdock	<i>Arctium lappa</i>
	Wild onion	<i>Allium</i> spp.
	Common amaranth	<i>Amaranthus retroflexus</i>
	Spotted knapweed	<i>Centaurea maculosa</i>
	Wild carrot	<i>Daucus carota</i>
	Common mullein	<i>Verbascum thapsus</i>
	Deertongue	<i>Dichanthelium clandestinum</i>
	Tick-trefoil	<i>Desmodium</i> spp.
	Greenbrier	<i>Smilax</i> spp.
	Spiny amaranth	<i>Amaranthus spinosus</i>
	Purslane	<i>Portulaca oleracea</i>
	Watercress	<i>Nasturtium officinale</i>
	Creeping Charlie	<i>Glechoma hederacea</i>
	Jimsonweed	<i>Datura stramonium</i>
	Spotted spurge	<i>Euphorbia maculata</i>
	Silverleaf nightshade	<i>Solanum elaeagnifolium</i>
	Pokeweed	<i>Phytolacca americana</i>

Table 7. Percent cover of forages within treatments by species or groups

Year	Treatment ¹			SE	Tukey's-adjusted <i>P</i> -values ¹		
	BW	HL	OP		BW vs. HL	BW vs. OP	HL vs. OP
Tall fescue, %							
2014	36.2	58.9	62.2	2.0	<0.0001	<0.0001	0.9653
2015	32.8	66.6	68.8	2.0	<0.0001	<0.0001	0.9968
2016	38.8	74.8	70.2	2.0	<0.0001	<0.0001	0.7942
Average ²	35.9	66.8	67.1	1.2	<0.0001	<0.0001	0.9810
Orchardgrass, %							
2014	15.9	9.3	7.7	1.0	0.0006	<0.0001	0.9759
2015	7.1	5.4	4.6	1.0	0.9672	0.7444	0.9997
2016	8.2	4.2	4.3	1.0	0.1569	0.1998	1.0000
Average ³	10.4	6.3	5.5	0.6	<0.0001	<0.0001	0.6521
Kentucky bluegrass, %							
2014	3.3	0.2	1.8	0.6	0.0144	0.7671	0.5781
2015	5.0	1.1	2.1	0.6	0.0005	0.0259	0.9598
2016	7.8	4.2	4.3	0.6	0.0021	0.0041	1.0000
Average ³	5.3	1.8	2.8	0.3	<0.0001	<0.0001	0.1398
Red clover, %							
2014	4.8	13.6	7.3	1.1	<0.0001	0.7269	0.0023
2015	1.1	1.6	0.7	1.1	1.0000	1.0000	0.9995
2016	4.7	1.2	2.6	1.1	0.3298	0.8967	0.9893
Average ²	3.5	5.4	3.5	0.6	0.0683	0.9994	0.0735
White clover, %							
2014	4.9	8.6	4.4	0.9	0.0859	1.0000	0.0288
2015	3.8	7.6	3.1	0.9	0.0724	0.9995	0.0128
2016	2.1	1.2	1.3	0.9	0.9979	0.9995	1.0000
Average ²	3.6	5.8	2.9	0.5	0.0086	0.6180	0.0004
Hop clover, %							
2014	0.7	0	0.1	0.3	0.6306	0.7781	1.0000
2015	0.8	0.1	0.2	0.3	0.4723	0.6306	1.0000
2016	1.3	0	0.3	0.3	0.0094	0.0714	0.9986
Average ³	0.9	0	0.2	0.1	<0.0001	0.0008	0.7771
Broadleaf weeds, %							
2014	14.1	5.5	11.8	1.1	<0.0001	0.8783	0.0067
2015	11.6	11.2	14.6	1.1	1.0000	0.6474	0.4740
2016	9.5	8.8	11.4	1.1	1.0000	0.9577	0.8045
Average ²	11.7	8.5	12.6	0.7	0.0026	0.6286	0.0001
Warm season grasses, %							
2014	16.8	1.2	2.9	2.0	<0.0001	<0.0001	0.9994
2015	28.0	3.0	4.3	2.0	<0.0001	<0.0001	0.9999
2016	16.3	1.8	3.0	2.0	<0.0001	0.0002	0.9999
Average ²	20.4	2.0	3.4	1.1	<0.0001	<0.0001	0.6494
Horse nettle, %							
2014	0.8	1.8	2.5	0.8	0.9953	0.8952	0.9997
2015	0.8	6.8	6.9	0.8	0.0001	<0.0001	1.0000
2016	0.6	4.5	5.2	0.8	0.0381	0.0070	0.9997
Average ²	0.8	4.4	4.9	0.5	<0.0001	<0.0001	0.7484
Nutsedge, %							
2014	0.4	0	0	0.1	0.2697	0.2697	1.0000
2015	0.4	0.1	0	0.1	0.5724	0.2697	0.9999
2016	0.3	0.3	0	0.1	0.9999	0.5724	0.8646
Average ³	0.4	0.1	0	0.1	0.0158	0.0005	0.4962
Brome grasses, %							
2014	1.0	0	0	1.4	0.9998	0.9998	1.0000
2015	5.5	0.2	0	1.4	0.1351	0.1104	1.0000
2016	9.5	0.2	0.3	1.4	0.0002	0.0002	1.0000

Table 7. Continued

Year	Treatment ¹			SE	Tukey's-adjusted <i>P</i> -values ¹		
	BW	HL	OP		BW vs. HL	BW vs. OP	HL vs. OP
Average ²	5.3	0.1	0.1	0.8	<0.0001	<0.0001	1.0000
Sweet vernal grass, %							
2014	1.3	0.2	0.1	0.5	0.8419	0.7850	1.0000
2015	2.3	0.2	0.1	0.5	0.1236	0.0954	1.0000
2016	0.9	0.1	0	0.5	0.9745	0.9551	1.0000
Average ³	1.5	0.1	0.1	0.3	0.0066	0.0037	0.9806
Quackgrass, %							
2014	0	0	0.1	0.2	1.0000	1.0000	1.0000
2015	0.3	0.1	0.4	0.2	0.9975	0.9975	0.8370
2016	0.3	0.7	0.4	0.2	0.6054	0.9975	0.9645
Average ³	0.2	0.3	0.3	0.1	0.7853	0.5133	0.8979
Honeylocust, %							
2014	0	1.3	0.3	0.3	0.0205	0.9992	0.1187
2015	0	1.6	0	0.3	0.0025	1.0000	0.0025
2016	0	1.1	0.3	0.3	0.1187	0.9992	0.4233
Average ³	0	1.3	0.2	0.2	<0.0001	0.7297	<0.0001

¹Treatment: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

²Presented by year and by all years combined despite treatment × year interaction in statistical model.

³Presented by year and by all years combined because of no treatment × year interaction in statistical model.

Table 8. ADGs of lambs and total live weight gains (LWG) of treatments across three summers

Year	Treatment ¹			Tukey's-adjusted <i>P</i> -values ¹		
	BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
ADG ± SE, g·d ⁻¹						
2014	35 ± 7	38 ± 6	32 ± 6	1.0000	1.0000	0.9988
2015	56 ± 6	64 ± 5	48 ± 5	0.9816	0.9852	0.4632
2016	125 ± 6	87 ± 5	94 ± 5	<0.0001	0.0043	0.9762
Average ²	72 ± 3	63 ± 3	58 ± 3	0.1453	0.0134	0.5462
LWG ± SE, kg·d ⁻¹						
2014	4 ± 3	5 ± 3	3 ± 3	1.0000	1.0000	0.9997
2015	9 ± 3	13 ± 3	9 ± 3	0.9863	1.0000	0.9781
2016	17 ± 3	17 ± 3	18 ± 3	1.0000	1.0000	1.0000
Average ³	10 ± 2	12 ± 2	10 ± 2	0.7667	0.9999	0.7592

¹Treatment: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

²Presented by year and by all years combined despite treatment × year interaction in statistical model.

³Presented by year and by all years combined because of no treatment × year interaction in statistical model.

those systems. Fannon et al. (2019) also found more NDF in forage samples collected from the black walnut silvopastures but not the honeylocust silvopastures early in the growing season; there were no differences in NDF between pasture treatments later in the season. Data from studies in controlled environments are mixed. Kephart and Buxton (1993) reported small declines in NDF with increasing shade levels for C3 and C4 grasses, whereas there was no effect of shade on NDF concentrations among species tested by Lin et al. (2001). TDNs measured in orchardgrass along a woodland rose with increasing shade in the spring, but stayed about the same with variable levels of light during the summer (Belesky et al., 2006).

Forage Species Composition

The percent cover of tall fescue was lowest in the black walnut silvopasture, whereas the percent cover of orchardgrass was highest in these same systems. Orchardgrass, as the name implies, tends to have greater shade tolerance than tall fescue (Burner, 2003). Light availability is an important factor in the tillering capacity of grasses, but tillering in orchardgrass has been shown to be less affected by shade than tillering in tall fescue (Belesky et al., 2011).

Red clover populations declined rapidly in all systems from 2014 to 2015, likely due to the low

persistence of this species (Taylor, 2008). Percent cover of red clover increased in 2016 in the black walnut silvopastures, and more than in the other systems. This might be attributed to improved seed to soil contact and less competition following seeding in early March of 2016, as the canopy under black walnut silvopastures was more sparse. The white clover populations declined between the second and third years in the honeylocust silvopastures, perhaps due to a sheep preference for clover and thus selective overgrazing (Penning et al., 1997).

The reduced growth of tall fescue in the black walnut silvopastures provided space for more broadleaf weeds, warm season grasses, annual *Bromus* spp., and the short-lived perennial, sweet vernal grass. Efforts to control broadleaf weeds during the second year resulted in equivalent levels of broadleaf weeds among all three systems in years 2 and 3. However, the percent cover of warm season grasses and sweet vernal grass continued to be greatest in the black walnut silvopasture throughout all years. Percent cover of the annual *Bromus* spp. was greatest in the black walnut silvopasture only in the third year.

Horse nettle, a member of the Solanaceae family, was hardly present in the black walnut silvopastures compared to the other systems for all 3 yr. Juglone, the allelochemical secreted by black walnut trees, is known to inhibit the growth of some species within the nightshade, or Solanaceae family (Soderquist, 1973).

A common concern expressed regarding planting honeylocusts into pastures is that these trees are thorny (if not selected or grafted for thornlessness), competitive, and thus quick to spread and form thickets. Although honeylocust suckers and seedlings were most common in the honeylocust silvopastures, over the entire study there was no significant increase in percent cover of honeylocust, which was always less than 2% of the total sward cover. None of the honeylocust seedlings or suckers were observed to have thorns of any noticeable or potentially damaging size. In fact, the sheep selectively grazed the honeylocust stump regrowth, along with any new honeylocust volunteers in the sward, typically before consuming any other forage species.

Nutsedge, a plant requiring moist conditions for survival, was significantly more prevalent (although at minimal levels) in the black walnut silvopastures. The walnut trees produced the greatest levels of shade, which may have created an environment better suited for nutsedge.

Lamb Performance

Although lamb ADG in silvopastures was equal or greater than the ADG of lambs in open pastures for all 3 yr, it is more informative to compare total system animal gains due to the different stocking rates of the systems. The honeylocust silvopasture supported the same stocking rate as the open pastures, but the black walnut silvopastures, with lower available forage, supported fewer animals for all 3 yr. Nevertheless, the improved animal gain in the black walnut silvopastures offset the fewer animal numbers, leading to equivalent total animal productivity in all systems across all 3 yr.

Equivalent or better animal gains in silvopastures compared to open pastures are supported by other studies. In Tennessee, where black walnut trees were grown in bluegrass pastures, greater forage was produced under the mature trees, which corresponded with increased cattle gains (Neel, 1939). In Missouri, 3-yr-old silvopastures with deciduous hardwood tree species produced the same weight gains for heifers and cows compared to open pasture systems (Lehmkuhler et al., 2003), although these small trees had limited effect on forage supply. In contrast, heifers grazing rye and annual ryegrass established in a mature pine and black walnut silvopasture had similar gains to heifers grazing these forages in open pastures despite 20% lower forage productivity in the silvopastures (Kallenbach et al., 2006). In Virginia, on the same study site used as this study but about 5 yr earlier and prior to the final tree thinning, lamb gains did not differ between silvopastures and open pasture systems (Fannon et al., 2019).

Animal performance was low in the first 2 yr but improved in year 3. In the first year, the much larger and more mature lambs used required a higher plane of nutrition for additional growth and likely had lower growth rates. Although lambs were smaller and younger in the second year, performance was low due to high parasite infection levels and poor recovery in some lambs following deworming treatment, which may indicate parasite resistance to medication. A hardier hair sheep cross was used in the final year, and gains were high for all treatments.

CONCLUSION

Black walnut and honeylocust silvopasture systems supported equivalent lamb live weight gains compared to the open pastures. In the case of the black walnut silvopasture, this occurred despite

reductions in forage productivity and despite the presence of some less desirable species compared to open pastures. In the case of the honeylocust silvopastures, there were slight benefits to forage productivity and nutrition (greater N and lower NDF concentrations). Similar animal output compared with conventional open pastures, coupled with potential timber and tree crops, indicate these silvopasture systems may be more productive than traditional pasture systems.

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