Lamb performance, behavior, and body temperatures in hardwood silvopasture systems

by

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Abstract (Academic)

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Trees in silvopastures may provide forage-livestock systems with multiple goods and services, including shade, shelter, and browse. Reports of forage and animal productivity from these systems indicate that, in some cases, animal gains are similar or better despite lower forage yield. The relationship between grazing system, body temperature, grazing behavior, and animal performance was explored in this study. Black walnut and honeylocust-based silvopasture systems were compared with open pastures in a randomized complete block design (*r* = 3) over three summers. Pastures were rotationally stocked with 5-7 lambs depending on forage availability. Lambs were weighed every four weeks. Behavior measures were recorded within a replicate within a week, and these measures were taken sequentially within three experimental periods. Ewe lambs (*n* = 3) were equipped with a vaginal temperature sensor (3 days) and an audio recording device (1 day) to detect prehension events. Cameras documented lamb behavior every 60 seconds. Forage measurements taken with a rising plate meter indicated greater productivity in the honeylocust silvopasture (5020 ± 30 kg · ha^{-1}) compared to the open pasture (4930 ± 30 kg · ha^{-1}; $P = 0.0281$), though forage availability in the black walnut silvopastures (3560 ± 30 kg · ha^{-1}) was lower than within the other treatments ($P < 0.0001$). There was no difference in animal gains between systems ($P \geq 0.4813$), though gains were highest in the honeylocust silvopastures (25.6 ± 3.4 kg · $period^{-1}$), followed by the gains of the black walnut silvopastures (22.3 ± 3.4 kg · $period^{-1}$), and the gains of the open pastures (22.2 ± 3.4 kg · $period^{-}$

^{1}). Lambs in silvopastures spent more time lying down than animals in the open pastures ($P \leq 0.01$), while lambs in the open spent more than two hours longer each day standing ($P < 0.0001$). During the hottest part of the day, ewes in the open pasture were 0.4 °C hotter than ewes in the black walnut silvopastures ($P \leq 0.0202$). Lambs in the black walnut silvopastures grazed more (488 ± 14 minutes $\cdot$ day^{-1}) than lambs in the honeylocust silvopastures (438 ± 15 minutes $\cdot$ day^{-1}; $P = 0.0192$) and the open pastures (417 ± 14 minutes $\cdot$ day^{-1}; $P = 0.0009$), with no difference between the latter two systems ($P = 0.3073$). There was no difference in daily bites taken ($P \geq 0.7222$), though lambs in the silvopastures grazed more frequently than lambs in the open pastures.

In one six week winter grazing study, animal performance in the honeylocust silvopastures was compared with the productivity of lambs grazing the open pastures and the black walnut silvopastures. The objective of this study was to determine the effect of these pods on lamb growth when animals grazed stockpiled tall fescue (*Schedonorus arundinaceus*). Pre- and post-graze forage mass was estimated with a double sampling technique using a rising plate meter. Treatment pastures were rotationally stocked with three (walnut) or six lambs per experimental unit depending on forage availability. Fescue grab samples were collected every other rotation. Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and total digestible nutrients (TDN) were estimated with a robust equation using NIR spectroscopy. Pre- and post-graze pod mass per hectare was estimated using randomly placed quadrats. Lambs were naïve to pods and did not readily consume the fodder until four weeks into the trial, and the methods for estimating pod intake were not sufficient to detect pod differences in pre- and post-graze pod mass. Forage availability in the honeylocust silvopastures (5130 ± 90 kg $\cdot$ ha^{-1}) and open pastures (5050 ± 90 kg $\cdot$ ha^{-1}; $P=0.7580$) was greater ($P < 0.0001$) than forage

availability in the black walnut silvopastures (3790 ± 90 kg · ha^{-1}). Treatment had no effect ($P = 0.3763$) on average daily gains across the six weeks of the study. However, lambs within the honeylocust silvopastures had greater ($P = 0.0251$) average daily gains in the final period (0.12 ± 0.02 kg · day^{-1}) than lambs within the open pastures (0 ± 0.02 kg · day^{-1}), and lambs were observed consuming the pods. These data suggest that honeylocust pods may support greater gains of lambs, but that previous exposure and longer study periods in pasture settings may be necessary to see their nutritional benefit when grazing high quality forages.

Abstract (General Audience)

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Silvopastures – where trees are integrated into pasture systems – may provide forage-livestock systems with multiple goods and services, including shade, shelter, and browse. In some comparisons with open pasture systems, animal gains have been similar or better in silvopastures despite lower forage yield. The objective of this study was to determine whether changes in forage nutritive value or changes in lamb behavior during summer might compensate for lower forage productivity in honeylocust and black walnut silvopasture systems. Tree species had variable effects on forage characteristics and animal behavior, but lamb weight gains were similar across all treatments for three years. Forages in the honeylocust silvopasture systems were more productive and nutritious than forages in the open pasture systems. Forages were least productive and greater levels of weedy forage species were present in the black walnut silvopasture systems. However, greater shading in walnut systems kept the lambs cooler throughout the hottest parts of the day. Lambs in both silvopasture systems spent more time lying down and grazed more frequently than lambs in the open pastures. Lambs in the open pastures spent over two hours longer each day standing, indicating the level of heat stress they were experiencing.

Lamb weight gains were similar across all treatments in one winter grazing study. However, lambs were initially naïve to honeylocust pods. When the lambs finally began to eat the pods, their weight gains were greater than the weight gains of lambs in the open pastures,

suggesting that honeylocust pods may provide a nutritional benefit to lambs grazing stockpiled forages once they have acquired a taste for the pods.

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As I first drove up I-77 into Virginia, I never dreamed that I would marry a beautiful, virtuous woman and become a father to the happiest little girl before it was all over. Sarah Kate, thanks for your devotion, helping me bag forage in the August heat on Ada Mae’s due date. Ada Mae, I’m happy because you look like your mom; I’ll be overjoyed when you act like her, too.

Thank you, Lord: though the grass withers, your Word endures forever. *Soli Deo gloria*.

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List of Abbreviations

ADF – Acid detergent fiber

ADG – Average daily gain

ANOVA – Analysis of variance

BW – Body weight

CP – Crude protein

EU – Experimental unit

LWG – Live weight gain

n – sample size

N – Nitrogen

NDF – Neutral detergent fiber

NIRS – Near infrared spectroscopy

P – probability

R^2 – Multiple coefficient of determination

SD – Standard deviation

SE – Standard error

TDN – Total digestible nutrients

THI – Temperature humidity index

TNZ – Thermoneutral zone

Chapter 1: Literature Review

Introduction

Human population growth is increasing global demands for food and fiber production at the same time that the agricultural landbase and the resources for agricultural production are in decline (Pimentel et al., 1976; Tilman et al., 2002; Tilman et al., 2011). Concern about climate change and dwindling natural resources has led to a public push to decrease environmental contamination (Chen et al., 2011).

Agroforestry offers opportunity to fulfill the demands both for increasing food and fiber production, while also improving environmental quality through increased nutrient utilization, reduced sediment runoff and erosion, and increased carbon sequestration (Young, 1990; Nair, 1998; Wallace, 2000; Montagnini and Nair, 2004; Tscharntke et al., 2012). These diversified systems are managed so as to take advantage of positive interactions among system components and thus create greater output than monocultural production systems. Simple monocultures of pasture and animal systems have appealed to livestock producers in the past, as this simplifies management. However, the sustainability of such reductionist methods is being called into question (Lyson, 2002) and systems that take advantage of complexity and diversity are being seen as more productive and sustainable.

Silvopasture, one of five agroforestry practices, integrates trees with pasture-based livestock systems and provides both short- and long-term returns from the same land base (Sharrow et al., 2009). Livestock in silvopasture systems can benefit from shade in summer and shelter from wind in winter. Trees in turn benefit from the managed livestock presence through amplified nutrient cycling and weed suppression. Along with potential benefits to food and fiber production, silvopasture systems may have increased soil organic matter with improvements in microbial health and nutrient cycling (Chander et al., 1998), greater water storage (Sharrow, 2007), and improved nutrient capture and retention (Michel et al., 2007). These factors, coupled with improved soil conservation and nutrient utilization, result in regional watershed benefits (Shrestha and Alavalapati, 2004). Silvopastures sequester more carbon than timber plantations or pastures, an advantage with global ramifications (Sharrow and Ismail, 2004). Along with these production and environmental benefits, silvopasture systems may require less nutrient and herbicide inputs; increase and diversify marketable production; and produce aesthetically-pleasing landscapes that add value to farms and rural economies (Sharrow et al., 2009).

Animal and forage production in silvopastures

Maintaining adequate livestock production in silvopastures will be a primary concern to most producers because forage productivity can decline slightly in silvopastures (Buergler et al., 2005; Kallenbach et al., 2006; Kyriazopoulos et al., 2013). Despite resource competition between forages and trees, the decrease in forage quantity might be ameliorated by an increase in forage quality, whether that be a function of cooler temperatures under trees (Buergler et al., 2006) and delays in vernalization (Neel et al., 2016), or increased soil organic matter with improvements in microbial health and nutrient cycling (Chander et al., 1998), greater water storage (Sharrow, 2007), and improved nutrient retainage (Michel et al., 2007). However, lower soluble carbohydrates (Buergler et al., 2006) and only moderate, variable responses in terms of fiber digestibility (Fannon-Osborne, 2012) in other studies of silvopasture forages challenge this idea. Despite reductions in forage availability, most research has demonstrated no reduction in animal growth (Lehmkuhler et al., 2003; Kallenbach et al., 2006; Fannon-Osborne, 2012). As a result, all of the biomass produced by the trees represents the net biomass production of the silvopastures compared to open pastures. The higher land productivity of silvopastures may be reason enough for adoption in livestock production systems by landowners interested in intensive farm management.

Along with the potential to improve ecosystem functioning and quality, silvopastures can also enhance animal well-being through mitigation of environmental stressors such as thermal radiation and wind. Public society has become increasingly concerned with animal welfare in production agriculture as modern livestock agribusiness tends towards centralized livestock production methods and away from the traditional and respected pastoralism of the past (Fraser, 2014). Though a subjective term, some animal welfare principles are generally affirmed by the livestock industry, such as protection from environmental stressors (Lyles and Calvo-Lorenzo, 2014). Silvopastures provide an opportunity to manage livestock in an ecologically and economically sustainable manner, at the same time that the livestock are provided with a comfortable environment. Such an environment provides for the well-being of livestock, though the necessity of shade in maintaining animal productivity may be questioned.

Animal well-being, behavior, and productivity in silvopasture has not been well studied. The shade of the trees provides comfort and protection from summer heat and winter wind; the provision of shade in summer may result in increased animal gains (McDaniel and Roark, 1956). Heat load may change activities and intensify stresses experienced by animals in open pastures, thus increasing time and energy spent in behaviors to stabilize body temperature. Ambient temperatures are lower and less variable in silvopasture systems; thus, animals may experience more time with conditions suitable for grazing and increase dry matter intake (Mitlohner and Laube, 2003). Distinguishing between reduced energy needed for maintenance versus greater opportunity for grazing in pasture systems is challenged by the limited tools for monitoring grazing animals, and current methods involve time-intensive observations. Public concern over animal welfare is increasing; livestock producers can address these concerns with silvopasture adoption, but more information on animal behavior in silvopastures is necessary to properly conclude how trees affect animal welfare.

Ruminant response to heat stress in extensive conditions

Though heat stress can markedly decrease animal production in a confined dairy or feedlot setting, the negative effect of heat stress on animals in extensive grazing situations has not been well documented. In an economic simulation of the costs and benefits of applying different levels of heat abatement strategies, St-Pierre et al. (2003) found that intensive heat stress abatement strategies are optimal for dairy production in most of the United States. The costs for such strategies are lower in confinement settings than in pasture settings. Dairy cattle are also very susceptible to heat stress as they have high metabolic rates and consume energy-dense feedstuffs. In the case of beef cattle, however, they found little benefit in heat stress abatement strategies. Although perhaps surprising, the lack of evident benefits may have been obscured by low feed costs at the time. The national average of loss per steer due to heat stress was $12 per year. In the case of beef cows, the national average of loss per cow due to heat stress was estimated to be $2.60 per year. In the extensive conditions in which cows are typically raised, the cost for heat abatement strategies was found to be too high to warrant adoption. Beef cows, which are, in some cases, bred in the spring during a period of low heat stress, also have lower metabolic rates than dairy cows and thus have a lower Temperature Humidity Index (THI) threshold.

THI takes into account humidity and temperature conditions by the equation (Hubbard et al., 1999)

$$\text{THI}=\left(0.8\times\text{temperature (°C)}\right)+\left[\left(\frac{\text{\% relative humidity}}{100}\right)\times\left(\text{temperature(°C)-14.4}\right)\right]+46.4$$

An additional THI equation, using wet bulb temperature (W °C) and dry bulb temperature (D °C) is (Silanikove, 2000)

$$\mathrm{THI}=0.72\ (\mathrm{W}\ ^{\circ}\mathrm{C}+\mathrm{D}\ ^{\circ}\mathrm{C})+40.6$$

The expected THI threshold may be confounded by a lack of accurate data on the effect of heat stress on grazing ruminants in extensive pastured conditions (Silanikove, 2000). The THI threshold used by St-Pierre et al. (2003) represents the point where heat stress presumably occurs, though no data were presented to document this point. The definition of heat stress varies widely and threshold points can vary widely according to the chosen definition. In addition, due to a lack of published studies, St-Pierre et al. (2003) assumed negligible intake reduction for heat stressed cows on pasture, an assumption that may prove to be invalid further in this review.

The Thermoneutral Zone (TNZ) concept for livestock is used to understand the relationship of livestock with their environment and to define the point at which ambient conditions become detrimental to animal health and well-being. (Silanikove, 2000). Schematically, the TNZ is bounded by lower and upper critical temperatures points. The lower critical point occurs at the ambient temperature below which a homeothermic animal must produce heat to maintain a stable body temperature. The upper critical temperature is ambiguous and has been defined as the ambient temperature where the metabolic rate increases, evaporative heat loss increases, or tissue thermal balance is minimal (Mount, 1973). Respiration rate is perhaps the simplest field measurement to collect, but sweating can occur before an increase in respiration rate (Silanikove et al., 1997). For example, the upper critical temperature for horses (*Equus ferus caballus*) was 20 °C using an increased evaporative heat loss definition, 25 °C using an increased metabolic rate definition, , and 30 °C using a minimal tissue thermal balance definition (Morgan, 1998).

Although a standard measure for heat and humidity load, THI does not take into account radiation effects, which thus inhibits the capacity for detecting environmental differences between shaded and non-shaded sites. An improved measurement, the Black Globe Humidity Index uses the temperature inside an enclosed round black ball, which mimics temperature inside the body of an animal and is affected by thermal radiation. White dairy cows had lower maximum temperatures than black or black and white cows at a high Heat Load Index (HLI), which includes a black globe temperature measurement; this phenomenon was not observed at a high THI (Tucker et al., 2008). An Effective Temperature index was created by Yamamoto et al. (1994) using the respiration rate and body temperature of heifers as an indication of heat stress

$$\mathrm{ET}=0.24\ \mathrm{DBT}+0.76\ \mathrm{BGT}$$

DBT is the dry bulb temperature and BGT is the black globe temperature. This study indicates the relative impact that the BGT has on heat stress in ruminants compared to the DBT.

The Black Globe Humidity Index (BGHI) takes into account black globe temperature (BGT) and dew point temperature (DPT) in the equation (Buffington et al., 1981)

$$\mathrm{BGHI}=\mathrm{BGT}+0.36\times \mathrm{DPT}+41.5$$

The BGHI was designed to include radiant heat effects, but minimal adoption has limited its effectiveness (Collier et al., 2009).

The Wet Bulb Globe Temperature index (WBGT), often used in determining heat stress levels for humans, is simple to measure and takes into account thermal radiation effects (Budd, 2008). The temperature of a natural wet bulb (NWB), the temperature within a black globe measuring 15-cm in diameter (GT), and the temperature within a shaded, dry bulb (DB) are all used to calculate the index by:

$$\mathrm{WBGT}=0.7\ \mathrm{NWB}+0.2\ \mathrm{GT}+0.1\ \mathrm{DB}$$

When the equipment is housed in the shade, the equation becomes

$$\mathrm{WBGT} = 0.7\ \mathrm{NWB} + 0.3\ \mathrm{GT}$$

Given the broad assumptions of St-Pierre et al. (2003), the effects of heat stress on ruminants in extensive grazing conditions and the economic value of mitigating heat stress is not yet clearly defined.

Initial defense responses: increase vasodilation, respiration, and sweating

The initial defenses a ruminant employs against heat stress are sweating, vasodilation, and respiration (Silanikove, 2000). Homeothermy is typically maintained through these responses as long as temperatures do not rise above 25 °C for beef cattle (Hahn, 1999). If homeothermy is maintained under these conditions, stress is minimal and production is generally not diminished.

Evaporative cooling through sweating is the primary means of dissipating heat for a ruminant outdoors (Blackshaw and Blackshaw, 1994). As much as 85% of total heat loads was lost through evaporative and convective heat loss in *Bos indicus* cattle in a high radiative environment (Finch, 1986). For goats (*Capra aegagrus hircus*), sweating generally initiates before an increase in respiration rate as heat loads increase (Dmi’el and Robertshaw, 1983; Silanikove et al., 1997). However, whether cooling through sweating or panting is initiated depends on the heat source: under high radiation conditions, sweating is initiated because evaporative heat loss is more efficient while under high temperature conditions, panting is initiated because convective heat loss becomes more efficient (Dmi’el and Robertshaw, 1983). Under high radiation, about two-thirds of total heat loss was attributed to evaporation from the body surface.

About a third of the heat load on zebu cattle standing in the sun was actually produced by metabolic heat (Finch, 1976). The metabolic rate of *Bos taurus* breeds is higher, and they have fewer sweat glands and heavier coats, all of which increase the susceptibility of these breeds to heat stress relative to *Bos indicus* breeds (Blackshaw and Blackshaw, 1994). It is critical then for the internal heat produced by metabolism to be quickly transmitted to the surface of the animal where it can be lost through convection (through panting and wind) or evaporation (through sweating). Vasodilation facilitates this transfer of heat if internal temperatures are sufficiently higher than body surface temperatures (Finch, 1986; Blackshaw and Blackshaw, 1994).

Respiration rates or panting scores can indicate the thermal status of an animal, with higher rates indicating higher levels of heat stress as the animal attempts to dissipate heat through evaporation of water in the respiratory tract (Marai et al., 2007). Increased levels of panting dissipated 56% of the total heat production of shorn Merino sheep, indicating the importance of panting to maintain body temperatures (Hales and Brown, 1974); it is probably more important for unshorn sheep which have lower capacity for evaporative heat loss. However, it was estimated that for cattle, respiration only dissipated about 15% of body heat under high temperature conditions (Finch, 1986). Body temperature is well correlated to the panting activity of cattle, indicating the potential of using panting scores to quickly and effectively assess livestock heat loads (Gaughan and Mader, 2014).

Severe defense responses: reduce dry matter intake (DMI) and metabolism

When ambient temperature and humidity increases such that initial cooling mechanisms fail to maintain body temperatures, the animal has one last line of defense before body temperatures rise: reduce DMI and thereby lower the rate of metabolism (Silanikove, 2000). This is the point where heat stress has a direct effect on animal productivity.

A decline in feed consumption is a general trend for beef cattle (Ray, 1989; Gaughan et al., 2010; Blaine and Nsahlai, 2011) and dairy cattle (Blackshaw and Blackshaw, 1994; West, 2003) experiencing heat stress. This trend seems to hold true for sheep (*Ovis aries*). In a feedlot situation in Central Arizona, lambs of varying breeds (St. Croix, Karakul, and Rambouillet) all displayed reduced feed consumption and heart rates as temperatures increased across the season, although this did not result in reduced weight gains (Monty et al., 1991). Water consumption increased while feed consumption decreased for Awasi wethers experiencing an abnormal heat load (Bhattacharya and Hussain, 1974). In ruminants, heat stress is generally followed by a reduction in passage rate (Silanikove, 1992). Thus, appetite is indirectly suppressed through greater gut fill, but it is also believed to be directly suppressed by rising temperatures.

Sheep provided with higher levels of fiber in their diet displayed higher body temperatures than sheep provided with higher levels of concentrates (Bhattacharya and Hussain, 1974). Heat increment, the heat produced by metabolism of ingested food, is higher for more fibrous feeds and reducing fiber intake can reduce heat loads (Fuquay, 1981; Kurihara, 1996). Nevertheless, respiration, heart rates, and rectal temperatures all increased under heat loads for Awasi wethered sheep fed varying ratios of concentrate to roughage diets (Bhattacharya and Hussain, 1974). Reducing intake under heat stress conditions is believed to be an advantageous evolutionary development to reduce the heat increment associated with food metabolization.

To determine whether reductions in weight gains for calves was due to a direct heat stress effect or a reduction in DMI, O’Brien et al. (2010) pair-fed calves so that calves under thermoneutral conditions were fed the same amount of feed consumed by heat stressed calves. Reductions in intake due to heat stress fully accounted for the losses in gains. However, heat-stressed calves displayed higher basal and glucose-stimulated insulin concentrations, shifting metabolism from fatty acid metabolism to the more efficient glucose oxidation. This same phenomenon has been observed in lactating dairy cattle, and it is believed to be partially responsible for the significant losses in milk production under high heat stress conditions (Baumgard and Rhoads, 2012).

Final stage: increased body temperatures

If temperatures continue to rise past the animal's capacity to reduce internal heat load through reduced metabolism or if the temperature increase was too sudden for the animal to adapt by reducing DMI, the body temperature of the animal increases (Silanikove, 2000). Rectal temperatures are useful in determining the impact of severe heat stress. In one case, Hammond et al. (1996) distinguished the heat tolerance of different breeds of cattle by monitoring their body temperatures in Florida. Hereford and Angus calves had higher rectal temperatures than Senepol and Brahman calves, while Hereford calves with clipped hair had temperatures between those of unclipped Hereford calves and Senepol calves. Sheep in the thermoneutral temperature zone typically have rectal temperatures between 38.3 and 39.9 °C, and temperatures at or above 42 °C indicate that the sheep is experiencing severe heat stress that could lead to significant damage (Marai et al., 2007).

Dairy cows provided with lengthened night cooling conditions or lowered nighttime temperatures had average rectal temperatures that approached the rectal temperatures of cows in a thermoneutral environment more so than the rectal temperatures of cows with lower peak afternoon temperatures (Scott et al., 1983). This was interpreted as indicating that the nighttime dissipation of stored body heat is more important than lower daytime temperatures at maintaining body temperatures.

The bottom line: reduced performance

Though the negative effect of heat stress on the milk yield of dairy cows and the weight gains of calves and lambs in confinement is well established, the impact of heat stress on ruminant performance has been less studied in non-controlled, pasture situations where it is more difficult to remotely collect animal core body temperatures (Morrison, 1983). The capacity for measuring rectal temperatures in free-range livestock is limited to equipment that can automatically log and transmit or store the data. The effectiveness of rectal measurements is also limited by the tendency of rectal thermometers to restrict fecal matter flow. On the other hand, vaginal temperature sensors have been designed to be left in free-ranging cows for extended periods of time with little interference on the animal (Burdick et al., 2012). Vaginal temperature – although limited in use to cows, ewes, or does – was found to be well correlated with rectal temperature and other measures of core body temperatures.

The effect of heat stress on milk yield of dairy cattle is more pronounced than the effect of heat stress on growing beef cattle, and in some cases heat stress can reduce milk yield by 30% (West, 2003; Baumgard and Rhoads, 2012). This a result of multiple physiological and managerial differences, including lower metabolic heat production in beef cattle, the shift from fatty acid to glucose metabolism under heat stress, and the typical spring breeding period for beef cows when temperatures are mild (St-Pierre et al., 2003; Baumgard and Rhoads, 2012). Beef cattle have also been shown to make compensatory gains when hot weather passes (Baccari et al., 1983; Mader et al., 1999). Nevertheless, heat waves can reduce beef cattle gains and can have devastating impacts on the feedlot industry (Ray, 1989; Hahn, 1999; Mader, 2003). Though it might be assumed that heat stress impacts extensive ruminant operations in a similar manner, the extent to which it does so is relatively unknown.

In one of the few studies examining the effects of THI on livestock performance under extensive management conditions, Amundson et al. (2006) studied ten years of calving records and weather information to determine the THI threshold (inflection point of a 3-degree polynomial equation relating THI to pregnancy rate) at which cattle could no longer physiologically adapt to heat stress and pregnancy rates declined. At 21 days before conception, the THI threshold was 62.6; at 60 days before conception, the THI threshold was 72.9. These data indicate that conditions closer to breeding have more of an impact on conception rates. In contrast, the THI threshold for beef cows utilized by St-Pierre et al. (2003) was 75.

In another study of beef cattle conception and embryonic development, Biggers et al. (1987) found that although heat stress did not impact conception rates, conceptus weights were lower for heat stressed cows. In this case, three treatments were initiated eight days after breeding on three groups of Hereford and Hereford-Angus cows for eight days, including a control treatment (THI = 66), a high humidity and high temperature treatment (THI = 85 and THI = 80 for 12 hours each), and a low humidity and high temperature treatment (THI = 82 and THI = 78 for 12 hours each). It was believed that treatments may have altered pregnancy rates if complete gestation had occurred before conceptus collection.

Such observations also have been corroborated by studies of ewe placental development (Regnault et al., 2002). Vascular growth factors were shown to be diminished under increased core body temperatures early in gestation, thus reducing placental growth. For ewes on pasture, heat stress during the first 17 days of gestation led to a significant reduction in flock pregnancy rates (Soto et al., 1998).

In addition to reduced estrous duration and plasma estradiol levels and increased plasma progesterone levels, ewes subjected to a daily gradual increasing of temperatures to a maximum of 44 °C for 35 days in a climatic chamber ate less, lost weight, and displayed lower body condition scores than ewes not subjected to heat stress (Indu et al., 2014). Shorn wethered lambs also had lower weight gains when subjected to heat stress in climate chambers (Ames and Brink, 1977). Daily gains declined for lambs housed at 20 °C compared to daily gains of lambs housed at 15 °C. At temperatures of 35 °C, gains of lambs declined to 21% the gains of lambs housed at 15 °C. Protein and feed efficiency also declined with increasing temperature. Lambs subjected to fluctuating temperatures 5, 10, or 15 °C above and below (12 hours each) a thermoneutral temperature (15 °C) had reductions in gain, though these reductions were no different than those of lambs exposed to stable conditions at the same temperature extremes (Giacomini, 1979).

Friesian calves fed concentrate rations and ad libitum rice straw hay in Egypt had marked decreases in intake and weight gains during the summer, although temperatures were not reported (Marai et al., 1995). Another study of Friesian calves subjected initially to a THI of 63 for three days and then 81 for three days in a climate chamber reported that calves lost 15% in total body solids after the stressful conditions (Kamal and Johnson, 1971).

The research available on the effects of ruminants in extensive conditions demonstrates the negative effects of heat stress on fetal development, conceptus size, pregnancy rate, estrous cycles, and weight gains. This information, although limited, is substantiated by the thorough documentation of the significant negative effect of heat stress on animals in confinement operations. For this and other reasons as explained in the introduction of this section, St-Pierre et al. (2003) may have underestimated the economic cost of heat stress on beef cow production. In addition, they may have overestimated the potential cost and benefits of potential heat stress amelioration strategies, as explained in the subsequent section through an analysis of the benefits of shade.

Effect of shade in mitigating livestock heat stress

Removing thermal radiation load on animals is more difficult than just providing shade as only about 30% of the total radiation on a sunny day comes directly from the sky (Kelly et al., 1950; Bond et al., 1967). Diffuse sky radiation and reflected radiation from the ground or other objects can contribute significantly to total thermal radiation and are not intercepted by overhead shade. The lower the shade source, the more diffuse and reflected radiation will be intercepted.

Livestock rely heavily on evaporative cooling to reduce heat loads and thus heat stress is more likely under humid, still conditions than dry, windy conditions. Air flow can be beneficial in reducing cattle heat loads, which may limit the usefulness of walls on shade structures (Ittner et al., 1955). Trees can increase humidity levels, but they also allow for improved air circulation and can cool surrounding air through evaporation of moisture from leaves, or transpiration (Shashua-bar et al., 2009).

Shade utilization and behavioral modifications in shaded systems

Using time scans of eight different herds of dairy cattle provided with varying levels of natural shade, (Schütz et al., 2014) found that shade use by the herd increased with shade availability. Strangely, cows with access to shade spent less time lying down than cows in open pastures. Tucker et al. (2008) also found that dairy cattle provided with shade spent more time standing while under shade structures, but there was no difference in time spent lying down or grazing for cows where shade was provided than for cows in open pastures. Kendall et al. (2006) reported that cows provided with shade had altered behavioral regimens, though the total time spent in a given activity was not different between treatments. These observations could be attributed to the limited areas covered with shade in these pastures. Nevertheless, shade use increased as the available protection from solar radiation was increased.

Cattle in a loblolly pine silvopasture in Florida spent more time grazing, while cattle in an open pasture spent more time loafing, which includes standing and walking (Karki and Goodman, 2010). The Distribution Evenness Index (DEI), a measure of animal distribution patterns, was higher in the silvopastures than the open pastures in most measurement periods, indicating that cattle in the silvopastures more evenly utilized forage and space resources. Shade was available to cattle in the open pasture in a designated “tree zone” and along some fencelines. The differing levels of thermal stress between microclimates, but also the greater forage sward mass, seems to have played a role in these behavioral differences. Solar radiation in the silvopasture was 14-58% lower than in the open pasture and relative humidity and air and soil temperatures were also generally lower in the silvopastures. McIlvain and Shoop (1971) reported on the technique of using shade structures to draw cattle to underutilized areas of the pasture. When shade is available in hot conditions, animals will utilize it.

Initial shade benefits: decreased vasodilation, sweating, and respiration

In the feedlot, beef cattle provided with shade have lower respiration rates than cattle without shade across breeds, species, and sex (Mitlohner et al., 2001; Gaughan et al., 2004; Gaughan et al., 2010).

Dairy cows without access to shade had higher panting scores and respiration rates than cows in the shade (Schütz et al., 2014). As the amount of available shade increased, so did the number of animals that utilized the shade while the proportion of cows in the herd with high panting scores decreased. It was concluded that increasing shade coverage benefited the animals by reducing competition for the shady spots and by increasing wind flow, which would enhance evaporative cooling. Previous work had also demonstrated that average respiration rates decreased with increasing amounts of shaded areas (Schütz et al., 2010). Cows became more aggressive, spent more time near shade and water, and had higher respiration rates when the weather became hotter in all treatments, but the changes were most severe in the shadeless pasture.

Because respiration rates and panting rate scores are the simplest and least-intrusive methods for documenting heat load, they have been preferred over indices based on extent of vasodilation or sweating rate. Unfortunately, as noted previously, sweating and vasodilation can occur before respiration rates begin to rise. Methods based on respiration rates might underestimate heat loads or the benefit of slightly cooler microclimates, such as might be provided under shade. In a study of the effect of shaded pens on the extent of sweating in horses, horses in the shade only exhibited sweating for 1.1% of the observations compared to 51.4% of the observations for the unshaded horses (Holcomb et al., 2013). Respiration rates and body temperatures were also higher for the nonshaded horses. Certainly sweating is easier to document with horses than cattle or sheep. Nevertheless considering the evidence that sweating and vasodilation generally occur before an increasing in respiration, it might be assumed that shade use can lead to significant reductions in sweating rates and vasodilation.

Shade sometimes increases time spent grazing, but may not effect DMI

Mitlohner et al. (2001) studied the effect of shade and misting treatments in feedlot pens on 48 Angus-crossbred and 32 Charolais-crossbred heifers. The cows with shade had more efficient, or lower, feed to gain conversions and also had higher levels of DMI. Other studies in feedlots also demonstrated that the intake of beef cattle increases when shade is provided (Gaughan et al., 2010; Blaine and Nsahlai, 2011). The effect of shade on the intake and grazing patterns of cattle in pastures is less clear, however.

Dairy cattle with access to 3.6-m^2 shade · cow^{-1} grazed less during the daytime but not over 24 hours than cows without shade (Kendall et al., 2006). Cows with access to 2.4- or 9.6-m^2 shade · cow^{-1} displayed no difference in daytime grazing behavior than cows without shade (Schütz et al., 2010). Even when shade use increased with increasing levels of solar radiation protection, the amount of time cows spent grazing in these different treatments over 24 hours did not differ from the amount of time cows without shade spent grazing (Tucker et al., 2008). Contradictory results between pasture studies may be a result of variable levels of provided shade. More importantly, however, feed was abundant for the dairy cattle in all of these studies and in some cases, concentrate feeds were provided as a supplement to the forages. Shade may be more important for cattle where forage swards are thinner, nutrition might be limiting, or cattle need to spend more time grazing to maintain productivity.

In a Florida loblolly pine silvopasture, cattle spent 36-52% more time grazing than cattle in treeless pastures (Karki and Goodman, 2010). This behavioral difference may have been attributed to lower forage swards in the silvopasture; the cattle in the silvopasture may have had to compensate for lower forage intake per bite by increased grazing time. Unpublished potential DMI numbers indicate that the cattle in the open pastures may have had greater DMI despite less time spent grazing and more spent loafing. Though it was not believed that forage nutritive value played a role in DMI because nutritive value was sufficient for beef cow requirements, forages in the open pastures had higher levels of crude protein and TDN in March and June, but not September.

Ultimate benefit of shade: decreased body temperatures

For dairy cattle provided with differing levels of shade while on pasture, there were no differences in maximum body temperatures or diurnal temperature patterns compared to dairy cattle without access to shade (Tucker et al., 2008). Cows provided with structures that blocked 99% of solar radiation had minimum body temperatures 0.2 °C lower than cows without access to shade structures. This might be attributed to cows with shade being able to dissipate heat more efficiently in the evenings.

In a New Zealand pasture, dairy cows grazing during the summer months had significantly lower mean vaginal temperatures when provided with shade (38.6 °C versus 38.7 °C) despite relatively mild weather during the study (Kendall et al., 2006). The greatest differences occurred, as expected, during the hottest part of the day. Similar results were reported in another temperate environment study on dairy cows (Fisher et al., 2008). Body temperature benefits from shade were even more dramatic in subtropical Florida, where dairy cows provided with shade was 38.9 °C compared to 39.4 °C for dairy cows without shade (Roman-Ponce et al., 1977).

Dairy cattle provided with two different amounts of shade had slightly lower body temperatures (38.4 °C) than cows without any shade (38.5 °C) (Schütz et al., 2010). When temperature and humidity increased during the study, the body temperatures of all the cows in the study also increased, but the slope of increase for cows in the heaviest shade treatment (9.6-m^2 shade · cow^{-1}) was lower than the slope of increase for cows in the moderate (2.4-m^2 shade · cow^{-1}) and no shade treatments. An adequate amount of shade to accommodate all animals during periods of heat stress is important, but the appropriate amount of shade provided per animal was unfortunately not identified.

In a feedlot, cattle had lower daytime body temperatures when provided with shade than cattle in direct sunlight (Brown-Brandl et al., 2005). However, during the nighttime, cattle in the shaded treatments had higher body temperatures, perhaps because the shade structures blocked the night sky thereby limiting convectional heat loss. This phenomenon also occurred with dairy cattle, though in this it was assumed that the cattle could lose heat directly to the night sky because of the limited area covered by the shade structures (Fisher et al., 2008). It was believed that shaded cows might have displayed higher nighttime body temperatures because they spent more time grazing at night than unshaded cows. An alternative explanation was provided that unshaded cows were unable to revert to normal physiological conditions when temperatures began to drop in the evening and remnant effects of vasodilation or other cooling mechanisms lasted into the night. However, this is unlikely because vasodilation occurs in skin blood vessels for two reasons: heat weakens the binding strength of contractile agonist receptors on smooth muscles and heat directly dilates vessels while cool temperatures cause constriction (Sawka et al., 2011). Thus, vasodilation quickly responds to local temperatures through these direct modes of action.

The bottom line: improved performance

In controlled environments such as the feedlot, studies have consistently demonstrated weight gain improvements for steers when they are provided with shade (Boren et al., 1961; Gaughan et al., 2010) or at least more efficient gains (Sullivan et al., 2014). In the aforementioned feedlot study on shading and misting treatment effects, it was found that cows with shade reached target rates faster and had 12% higher average daily gains (ADG) than cows without shade (Mitlohner et al., 2001). (The misting treatment did not have an effect on animal performance). In Nebrasaka, weight gain improvements only occurred when shade was provided in areas with windbreaks, whereas there were only initial performance improvements when wind was not blocked indicating that the cattle can acclimate to stressful conditions when airflow is adequate (Mader et al., 1999). The benefit of shade depends on the magnitude of stressful conditions and the availability of alternative mechanisms for cooling.

A similar shade effect has been demonstrated in both confined and extensive dairy operations (Blackshaw and Blackshaw, 1994; West, 2003). In fact, due to the relatively low costs and direct benefits of shade on milk production, shade is considered imperative in confined dairy operations in the southeastern US. Though costs are higher to provide shade for pasture-fed dairy cows, productivity will also be higher. In Florida, artificial shade structures provided to dairy cows on bermudgrass (*Cynodon dactylon*) pastures lower vaginal temperatures and respiration rates, and a subsequent increase in milk yield and conception rates was reported (Roman-Ponce et al., 1977). Even in a temperate environment, summer milk production was higher for dairy cows on pasture when shade was provided (Fisher et al., 2008). Milk yield was greater for cows provided with artificial shade, though there was no difference between the herds in time spent grazing (Kendall et al., 2006). In this study, THI never rose above 74. The benefits of shade on productivity occurs at lower levels of heat stress than might be expected, considered the claim that mild heat stress occurs at a THI of 75-78 (Silanikove, 2000).

In one of the earlier controlled experiments on the effect of shade in a pasture on livestock weight gains, McDaniel and Roark (1956) tested the effects of two different levels of natural shade to artificial shade and no shade on the growth of Hereford and Aberdeen-Angus cows and calves. Cows and calves under natural shade gained significantly more weight than their counterparts that did not have access to shade. Calves under artificial shade, but not cows, also gained more weight than their counterparts without shade. Unfortunately, the conditions of the pastures was not reported, although the authors mentioned that conditions were similar across shade treatments. As a result, it is difficult to associate shade affects directly to weight gain improvements.

When shade structures were provided to steers in the summer while grazing on Oklahoma rangeland, they gained 9-kg · head^{-1} each summer more than steers without available shade (McIlvain and Shoop, 1971). In this case, range conditions were presumably similar for the shaded and non-shaded groups for the entire four year study. Shade structures were strategically placed and rotated to improve range utilization, indicating the preference of cattle for shade and the management opportunity that shade can provide in extensive situations.

Conclusion

Though the benefits of shade to animal productivity in intensive beef-finishing programs or confined dairy operations is apparent, the benefits of shade on animal productivity in extensive settings are not clear. In addition, studies of the benefits of shade should not focus merely on animal productivity, but also on animal welfare. Alternative indices of levels of heat stress, including sweating rate, vasodilation, or panting scores, should be considered in monitoring animal comfort as these responses generally occur prior to reductions in animal productivity. Changes in animal body temperatures and DMI indicate levels of heat stress that will likely have a negative impact on animal productivity, although the long term effect may be minimized by a species' potential for compensatory gain. Shade should be considered as a potential means for alleviating the effects of hot ambient conditions on animal welfare and productivity, though shade should be well-distributed to improve site utilization and sufficiently available to all animals in the pasture to minimize agonistic behavior. Such characteristics should be met in silvopasture systems, although the effects of tree shade in silvopastures on animal welfare remains to be studied.

Chapter 2: Forage productivity, nutritive value, and species composition in hardwood silvopastures and associated lamb productivity

Abstract

Integration of trees into pasture systems can have variable effects on forage and animal growth. Some studies have indicated that animal gains are similar or better despite lower forage yield. In this study, black walnut- and honeylocust-based silvopasture systems were compared with open pastures in a randomized complete block design with three blocks over three summers. Pastures were rotationally stocked with 5 to 7 crossbred lambs depending on forage availability. A rising plate meter was used to estimate pre- and post-graze forage mass. Forage grab samples of the mixed sward and of pure orchardgrass (*Dactylis glomerata*) 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 twelve points within each experimental unit every four weeks during the study. Pre-graze herbage mass tended ($P = 0.0717$) to be greater in honeylocust silvopastures (5020 ± 30 kg · ha^{-1}) than in open pastures (4930 ± 30 kg · ha^{-1}) and lowest ($P < 0.0001$) in the black walnut silvopastures (3560 ± 30 kg · ha^{-1}). Forages in the black walnut and honeylocust silvopastures had similar ($P = 0.4867$) N concentrations (23.3 ± 0.4 g · kg^{-1} and 23.9 ± 0.4 g · kg^{-1}, respectively), which was greater ($P \leq 0.0003$) than that of the forages in the open pastures (21.0 ± 0.4 g · kg^{-1}). Forages in the honeylocust silvopasture had lower ($P \leq 0.0042$) NDF concentrations (506.5 ± 3.4 g · kg^{-1}) than forages in the black walnut silvopasture and open pastures (mean = 525.0 ± 3.4 g · kg^{-1}). Forage species present in the black walnut silvopastures differed from those present in the open and honeylocust systems, which were similar in composition. Total lamb weight gains per system in

a 4 week period did not differ ($P \geq 0.7592$) among honeylocust, black walnut, and open pasture systems (10 ± 2, 12 ± 2, and 10 ± 2 kg · period^{-1}, respectively).

Introduction

Silvopasture is an agroforestry practice which integrates trees and livestock systems, providing both short- and long-term returns from the same land base (Sharrow et al., 2009). Livestock in silvopasture systems can benefit from shade in summer and shelter from wind in winter. The trees in turn benefit from the managed livestock presence through amplified nutrient cycling and suppression of weedy or invasive species. Along with potential benefits to increased food and fiber production, silvopasture systems may have increased soil organic matter with improvements in microbial health and nutrient cycling (Chander et al., 1998), greater water storage (Sharrow, 2007), and improved nutrient retainage (Michel et al., 2007). These factors, coupled with improved soil conservation and nutrient utilization, result in regional watershed benefits (Shrestha and Alavalapati, 2004). Silvopastures sequester more carbon than timber plantations or pastures (Sharrow and Ismail, 2004). Along with environmental benefits, silvopasture systems may also require less nutrient and herbicide inputs; 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 a primary concern for most livestock producers because forage productivity slightly declines in some systems (Buergler et al., 2005; Kallenbach et al., 2006; Kyriazopoulos et al., 2013). Despite resource competition between forages and trees, the decrease in forage quantity might be ameliorated by an increase in forage nutritive value, whether that be 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 terms of fiber digestibility (Fannon-Osborne, 2012) in silvopasture forages challenge this idea. Despite reductions in forage availability, most research has demonstrated no reduction in animal growth (Lehmkuhler et al., 2003; Kallenbach et al., 2006; Fannon-Osborne, 2012). Increased overall productivity might be reason enough for silvopasture adoption in livestock production systems. 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 three-year, 12-week summer grazing study was conducted in summers of 2014 through 2016. The work was conducted at the Whitethorne Agroforestry Demonstration Center at Virginia Tech's Kentland Farm in Blacksburg, Virginia (37.20 N 80.58 W). Soil series on the site include Berks-Lowell-Rayne complex, Unison and Braddock soils, and Weaver soils, arranged in order of decreasing slopes from 25-65%, 15-25%, and 0-5%, respectively.

Weather

Weather data were collected from a weather station located on Kentland Farm, about 500-m from the study site. Variables included air temperature (°C), relative humidity (%), gross radiation ($\mathrm{kW \cdot m^{-2}}$), and precipitation (0.01-in.). Temperature Humidity Index (THI) was calculated according to Mader et al. (2006)

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

where AT is air temperature (°C) and RH is relative humidity (%) measured by the Kentland Farm weather station. Historical weather data (1981 - 2010) was collected 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, including black walnut- (*Juglans nigra*) and honeylocust- (*Gleditsia triacanthos*) based silvopasturse, and open pasture treatments had been established in what was a uniform cool-season forage based pasture in 1995. The trees were thinned to a final density in 2012. After final thinning, trees were arranged in an approximate 12.2-m x 12.2-m configuration, with about 36-stems · ha^{-1}. Open and silvopasture treatments were replicated three times across the site in a randomized complete block design. The total area of each experimental unit (EU) was 0.27-ha · EU^{-1}, and each EU was subdivided into eight subpaddocks 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 grazed the site for six weeks as part of a second study during fall 2015.

Nitrogen was applied as urea in May 2014 and 2015 at a rate of 67-kg · ha^{-1}. Pastures also were fertilized for a stockpiling study in fall 2015, thus no fertility was added in spring 2016. Red and white clovers (*Trifolium pratense* and *T. repens*) were broadcast in all EUs at a rate of 4- and 1-kg · ha^{-1} respectively in the winter of 2013, and red clover was broadcast in all EUs at a rate of 4-kg · ha^{-1} in the beginning of 2016. Due to undesirable species and associated low productivity in the black walnut silvopastures, 1.3-kg of tall fescue (*Schedonorus arundinaceus* cv. Kentucky 31) and 0.3-kg of orchardgrass (cv. Benchmark+) were broadcast over each black walnut silvopasture EU after the second summer, followed by two passes with a drag harrow.

For stickweed (*Verbesina occidentalis*) control, all subpaddocks in block one, and all black walnut and four (half of the total) honeylocust silvopasture subpaddocks in block two, were treated with GlyStar Plus (Albaugh, LLC, Ankeny, IA). The herbicide treatment 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 re-treated after sheep were removed from the site in year two (2015). This time, all pastures were clipped to 13-cm and 10 days later all black walnut silvopasture systems and the open system in block one were treated with 5-L $\cdot$ 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 systems were spot-sprayed with the same herbicide mixture using a backpack sprayer. Early in summer 2016, all paddocks were spot sprayed with 23-mL $\cdot$ L^{-1} Weedar 64 2,4-D amine broadleaf herbicide (Nufarm Ltd., Laverton, Australia) using a backpack sprayer, targeting stickweed, creeping thistle (*Cirsium arvense*), milk thistle (*Silybum marianum*), blackberry (*Rubus* spp.), autumn olive (*Elaeagnus umbellate*), 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 purchased from a farm in Pulaski County, VA. They received a booster vaccination for *Clostridium perfringens* and a dose of anthelminthic medication (May 9, 2014). Lambs were maintained as a single group on open (non-treatment) 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 borrowed from a farm in Pulaski County, VA. Ram lambs were banded and all sheep were dosed with 8.8 mg · kg^{-1} BW of Prohibit Levamisole Drench solution (AgriLabs, St. Joseph, MO) and given a booster vaccination for *Clostridium perfringens* (May 22, 2015). They grazed the adjacent pasture for eight days before study initiation (May 30, 2015). At eight weeks (July 23, 2015), the lambs' level of anemia was scored based on 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, St. Joseph, MO). 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 borrowed 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) and 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' level of anemia was scored based on their lower eyelids according to the FAMACHA protocol as described by Kaplan et al. (2004). Any lamb with a score of 3 or greater received 8.8 mg · kg^{-1} BW of Prohibit Levamisole Drench solution. The same deworming protocol was followed every two weeks thereafter.

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

Stocking Rate and Methods

Each year, lambs were stratified by sex and body weight (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 experimental units.

Proportional stocking rates for each treatment within years were set based on proportional herbage availability and expected consumption over a 4-6 day grazing period assuming 20% utilization of available forage and intake rates of 3% of BW. Forage mass was estimated just prior to study initiation each year and stocking rates were set at this time. 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, while 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, while 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, while the remaining two treatments were stocked with five ewes and two wethers.

Sheep in all EUs were moved simultaneously to a fresh subpaddock once average residual forage heights reached about 7-cm. At the start of each rotation, sheep were allowed access to the half of the subpaddock where water was available. After about a third of the expected time (about 1-2 days) needed to graze a complete subpaddock had elapsed, sheep were provided access the remaining (ungrazed) portion of the subpaddock Although this allowed the sheep to back-graze, this was necessary to provide water access. Back-grazing generally lasted 2-4 days.

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 replacement sheep were included in subsequent period BW analyses. A livestock crate was used to confine lambs during weighing on Tru-Test load cells (Tru-Test, Ltd., Aukland, NZ). Average BW was calculated by averaging two un-shrunk BW measurements taken 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-week intervals was considered a single period.

Average daily gain (ADG) was calculated by dividing the average BW gain between periods by 28 days. System gain in a 4 week period was calculated by averaging the ADG of all healthy lambs in an EU and multiplying this by the total number of lambs within the EU and by 28 days. This approach was taken to correct for sick or deceased animals.

Forage Mass

Forage availability and residual mass were estimated by taking 30 random measurements within each of the nine subpaddocks with a rising plate meter (Jenquip, Fielding, NZ) 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 four days, 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 forage availability on entry and residual on exit. An estimate of forage disappearance per lamb was calculated as the difference between pre- and post-graze herbage mass divided by the total number of animals in the EU and the number of days in a given subpaddock.

Forage Nutritive Value

At every other rotation, mixed grass samples were collected between 1200 and 1400 h from each subpaddock before entry by lambs. Species and their proportions in the grab sample were selected roughly according to the relative proportion of their consumption by the lambs within the EU. Samples were cut at a 5- to 8-cm residual height. During the second and third years, an additional sample containing only orchardgrass also was collected at the same time.

Samples were dried in a forced air oven at approximately 55 °C for at least four days. 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, Eden Prairie, MN) using ISIscan software (FOSS North America, Eden Prairie, MN). Using WinISI software (FOSS North America, Eden Prairie, MN), samples from the first two years were grouped by similarity and representative samples were selected for further analysis of 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. (Vogel et al., 1999). All samples were run in duplicate. Samples were considered for re-analysis if the coefficient of variation exceeded 4%. Total nitrogen (N) was estimated using a Vario MAX CNS elemental analyzer (Elementar, Langenselbold, Germany). Single samples were run for analysis of N.

Forage Species Composition

Twelve randomly distributed points within each EU were marked at set distances from a selected fence post. A 0.5-m by 1.0-m quadrat was arranged square with the fence and placed at the set point. A modified Daubenmire approach (Daubenmire, 1959) was used to rank each species present in six cover classes. These classes included 1 (0-2.5%), 2 (2.6-25%), 3 (26-50%), 4 (51-75%), 5 (76-97.5%), and 6 (97.6-100%). 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.

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 Inst., 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 ANOVA of ADG and system gain, pre- and post-graze forage herbage mass and intake estimates, forage N and NDF content, and species composition by species between treatments was analyzed with PROC MIXED in SAS Studio, v. 3.5 (SAS Inst., Cary, NC). The study was conducted as a randomized complete block design with three replications. Year was included as a random effect. Repeated measures analysis by period was used with a compound symmetry covariance structure for the analysis of ADG. Repeated measures by sampling date was used with a standard variance covariance structure for the analysis of species cover, pre- and post-graze forage mass, intake, and nutritive value of mixed grass and orchardgrass samples. LS-means and Tukey's adjusted differences were calculated. Differences were considered significant when $P < 0.05$ and were reported as trends when $P < 0.10$.

For the analysis of species composition differences in percent cover, all warm season grasses (C4) 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 (*T. campestre*)] and honeylocust suckers or seedlings. Horse nettle (*Solanum carolinense*) was included in the broadleaf weed category, but also analyzed separately.

Results

Weather

Temperatures during the summer of 2014 were similar to or cooler than the historical average. Summers of 2015 and 2016 had hotter average minimum and maximum temperatures than the historical average (Table 2.1). 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. 2.1). Although conditions were within uncomfortable (70.0-74.9) and stressful (75.0-79.9) bounds throughout most of each summer, 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 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. In 2014, the maximum THI was 79.7, 80.1, 79.0, and 79.4 for June, July, August, and September, respectively. In 2015, the maximum THI was 75.4, 80.6, 80.4, and 79.1 for May, June, July, and August, respectively. In 2016, the maximum THI was 76.7, 79.9, 83.3, and 81.0 for May, June, July, and August, respectively.

In terms of solar radiation, on average, 2015 had sunnier days than the other two years (Fig. 2.2). Solar radiation was similar in 2014 and 2016.

As mentioned previously, spring was dry for all three years compared to the historical averages, and this was particularly the case in 2014 (Fig. 2.3). Despite a dry May in 2015 and 2016, conditions were generally stable for the latter three months of the study in those years.

Lamb Performance

In 2014 and 2015, ADG did not differ ($P \geq 0.4632$) among systems (Table 2.2), but in 2016, ADG was greater ($P \leq 0.01$) for lambs in black walnut silvopastures (treatment by 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, but there were no differences among treatments and no treatment x year interaction for total system output ($P = 0.8739$).

Forage Mass

The rising plate meter regression equations (Table 2.3) 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.

Greater forage production in the honeylocust silvopastures as compared to the open pastures in the third year and not the previous two years led to treatment by year interaction ($P = 0.0002$) for pre-graze forage availability as measured with the rising plate meter (Table 2.4). Throughout all three years, however, the black walnut silvopastures produced about 70% the forage mass produced in the honeylocust silvopastures and 72% the forage mass produced in the open pastures.

Although the stocking rate of the three systems was varied to keep post-graze residual herbage mass roughly equivalent across systems, the black walnut silvopastures consistently had a lesser amount of estimated residual mass than the other systems for all three years. There was also significant treatment by year interaction for post-graze forage biomass as measured with the rising plate meter ($P = 0.0070$).

Forage disappearance was greatest per lamb in the first year when the average lamb size was greater than in the last two years. However, there was no treatment by year interaction for disappearance per lamb ($P = 0.7326$), and over the three years, disappearance per lamb was greater in the black walnut silvopasture than in the open pasture.

Forage Nutritive Value

For the mixed grass sample, the R^2 for the NIRS prediction model for N was 0.9682 and for NDF was 0.8702. For the orchardgrass sample, the R^2 for the NIRS prediction model for N was 0.9689 and for NDF was 0.9402.

Forage N within the mixed grass samples was greatest all three years in the silvopastures, but decreased over time (Table 2.5). Forage N was lowest in the open pastures, particularly in the third year.

Forage NDF displayed treatment by year interaction ($P = 0.0089$). However, over the three years, forages within the honeylocust silvopastures had lower levels of NDF than forages in the black walnut silvopastures in the first two years and forages in the open pastures in the first year.

Forage N within the orchardgrass samples was adequate (National Research Council, 2007) for lamb growth for both years it was sampled (Table 2.6). The black walnut silvopastures had greater levels of orchardgrass N than the open pastures, while the orchardgrass in the honeylocust silvopastures tended to have greater levels of N than the orchardgrass in the open pastures.

There was no difference in orchardgrass NDF concentrations between treatments for both years.

Forage Species Composition

There was treatment by year interaction for percent cover of 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. ($P = 0.0197$). Percent cover of orchardgrass tended to display treatment by year interaction ($P = 0.0502$).

The percent cover of tall fescue (Table 2.7) fluctuated across the three years in each treatment, but was consistently lowest in the black walnut silvopastures, with no difference in percent cover of tall fescue between the remaining 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 two years 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. The warm season grasses included nimblewill (*Muhlenbergia schreberi*), johnsongrass (*Sorghum halepense*), yellow foxtail (*Setaria glauca*), crabgrass (*Digitaria* spp.), goosegrass (*Elusine indica*), and purpletop (*Tridens flavus*). The *Bromus* spp. included soft chess (*Bromus mollis*), downy brome (*Bromus tectorum*), and smooth brome (*Bromus inermis*). The broadleaf weeds are listed in Table 2.8, along with 14 unidentified broadleaf species.

Discussion

Lamb Performance

Although the ADGs of the lambs in the silvopasture were equal or greater than the ADGs of the lambs in the open pasture for all three years, 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 forage availability, supported fewer animals for all three years. Nevertheless, the improved animal gain in the black walnut silvopasture offset the fewer animals, leading to equivalent total animal productivity in all systems across all three years.

Equivalent or better animal gains in silvopastures compared to open pastures is supported by other studies. In Tennessee, where black walnut trees were planted in bluegrass pastures, there was an increase in the amount of forage produced under the mature trees along with corresponding increased gains of cattle grazing in the silvopastures (Neel, 1939). In Missouri, three-year-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). 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 five years earlier and prior to the final tree thinning, lamb gains did not differ between silvopastures and open pasture systems (Fannon-Osborne, 2012).

Animal performance was low in the first two years, but lamb ADGs doubled in the third and final year. In the first year, the much larger and more mature lambs used required a higher plane of nutrition for additional growth and were experiencing a leveling off in their 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 dosage with a deworming medication. As a result, a hardier hair sheep cross was utilized in the final year. In that year, gains were high for all treatments.

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 (Belesky et al., 2006; Buergler et al., 2005). However, under the black walnut trees, there was a 28% reduction in forage mass compared to the open pastures. Such evidence is supported by

Kallenbach et al. (2006) who measured 20% less ryegrass forage in 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 attempting to manage for equivalent residual 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 deflate forage mass predictions for the post-graze sward. Despite the apparent lower residual in these systems, the forages in the black walnut silvopastures produced the same levels of forage mass each year. Interestingly, the forage mass production of the honeylocust silvopastures increased each year, while the forage mass production of the open pasture decreased in 2015, and then increased in 2016. The forage productivity of the open pastures may have been more influenced by average precipitation levels during the months of the study, which were 356-, 265-, and 391-cm each year, respectively.

Across the three years, intake per lamb as estimated from herbage disappearance in the black walnut silvopastures consistently was higher than intake per lamb in the open pasture systems. Again, this number might be overestimated if the residual estimates were underestimated in the black walnut silvopastures. No difference in intake between the animals in the honeylocust silvopastures and the open pastures indicates that this might be the case. There are no other published comparisons of animal intake levels in silvopastures and open pastures, although cattle in shaded environments typically have greater intake (Blaine & Nsahlai, 2011; Gaughan et al., 2010; Mitlohner et al., 2001). The time that cattle in a Florida loblolly pine silvopasture spent grazing was greater than the time spent grazing by cattle in open pastures, though time spent grazing is not a perfect indicator of DMI and unpublished numbers indicate that the cattle in the open pastures may have had greater DMI (Karki and Goodman, 2010). This is a promising area for further investigation: if livestock consume less forage and yet have the same live weight gains in silvopastures, this would indicate that silvopastures can increase animal live weight gain efficiency.

Forage Nutritive Value

Forage N levels in the mixed grass samples steadily decreased in all treatments, although at different rates, over the three years. This coincided with the decrease in percent clover in all systems, which should have led to less N in the mixed grass samples as less clover was present in the systems. The orchardgrass samples also displayed a decrease in N concentrations between the second and third years (the only years in which they were sampled), although this might be a consequence of less N fixation in the systems as a result of declining clover populations or it could be attributed to the change in fertility application schedule. A spring application of N was made in the spring and then fall of 2015, instead of in both springs of 2015 and 2016.

Percent protein [percent crude protein (CP) = percent N x 6.25] available from the sward was adequate for lamb growth in the silvopastures (National Research Council, 2007), but inadequate for lamb growth (13.3% CP assuming a late maturing lamb gaining 100 g · day^{-1} and 20% rumen bypass protein in the forage) in the open pastures in the second and third year. With 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. Again, orchardgrass CP was adequate for lamb growth in both sampling years for all treatments. In this case, however, forage N only tended to be higher in the honeylocust silvopasture compared to the open pasture system. Nevertheless, there appears to be an effect of shade on N concentrations in these forages. An increase in silvopasture forage CP concentration has also been noticed by Kallenbach et al. (2006) in Missouri, although not by Fannon-Osborne (2012) 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 TDN:CP indicated that N content was disproportionately high in potential silvopastoral conditions (Belesky et al., 2006). In a containerized study of the effect of shade on various forage varieties, CP was generally elevated in forage grasses as shade levels increase (Lin et al., 2001).

NDF levels were lower in the honeylocust silvopastures than the open pasture in the first year, while the orchardgrass samples did not show any difference in NDF levels across all treatments for both years. This indicates that the difference in NDF is driven by species composition in the mixed grass 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 those systems. Fannon-Osborne (2012) also found lower NDF in mixed grass samples collected from the honeylocust but not the black walnut silvopastures early in the growing season; NDF was higher in the honeylocust silvopastures later in the year. In terms of within-species nutritive value, for most of the species tested in pots with increasing levels of shade, there was no effect of shade on NDF concentrations (Lin et al., 2001). TDN 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

While the percent cover of tall fescue was lowest in the black walnut silvopasture, the percent cover of orchardgrass was highest in these same systems. Orchardgrass, as the name implies, does tend to be more shade tolerant than tall fescue (Burner, 2003). The same might be possible for the bluegrass. Other work has demonstrated greater shading by black walnut trees than honeylocust trees (Brown and Gillespie, 1990; Buergler, 2004). However, in a controlled containerized study with increasing levels of shade, there did not appear to be a difference in the effect of shade on the aboveground productivity of the two tall fescue varieties, one of two orchardgrass varieties, and one of one bluegrass variety, although one variety of orchardgrass (var. Justus) had similar levels of productivity even at an 80% shade level (Lin et al., 2001).

Red clover populations declined rapidly in all systems from 2014 to 2015, which is not surprising considering the low persistence of this species (Taylor, 2008). Although there was an increase in the percent cover of red clover in 2016 in the black walnut silvopasture, there was not the same level of increase in the other systems. This might be attributed to improved seed to soil contact due to the lighter forage canopy in the black walnut silvopastures when the red clover was sowed in the first months of 2016. There were declines in white clover populations between the second and third years in the honeylocust silvopastures, perhaps a function of sheep preference for clover (Penning et al., 1997).

The reduced growth of tall fescue in the black walnut silvopastures provided space for more broadleaf weeds, warm season grasses, the annual *Bromus* spp., and the short-lived perennial, sweet vernal grass. Some effective control was made on the broadleaf weeds during the second year, leading to at least equivalent levels of broadleaf weeds between all three systems in years two and three. 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, in the Solanaceae family, was hardly present in the black walnut silvopastures compared to the other systems for all three years. Juglone, the allelochemical secreted by black walnut trees, is known to be particularly inhibitive of the growth of some species within the nightshade, or Solanaceae family (Soderquist, 1973).

A common concern for some interested in planting honeylocusts into a pasture is the competitive nature and quick spread of the species. Although honeylocust suckers and seedlings were more common in the honeylocust silvopastures than in the other systems for the entire study, there was no significant increase in percent cover of honeylocust over the study period, and the percent cover of this species 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, often prior to consuming any other forage.

Nutsedge, a plant requiring moist conditions for survival, was significantly more prevalent (although at minimal levels) in the black walnut silvopastures, which produce the greatest levels of shade, than in the other systems throughout the entire study.

Conclusion

These silvopasture systems supported equivalent lamb live weight gains compared to the treeless pastures. In the case of the black walnut silvopasture, this occurred despite reductions in forage productivity and thus animal carrying capacity, and also despite the presence of some less desirable species in these systems 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). Even with the potential products available from these trees, these silvopasture systems had similar animal output compared to the conventional open pastures.

Table 2.1. 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-year averages (1981-2010) at Kentland Farm, Blacksburg, VA.

	Year											
	2014			2015			2016			30-yr average		
Month	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	110.0
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

Table 2.2. Average daily gains of lambs (ADG) and total live weight gains of treatments (LWG) across three summers.

	Treatment[1]			Tukey's adjusted P-values[1]		
Year	BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
	---- ADG ± SE ($g \cdot d^{-1}$) ----					
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 ($kg \cdot period^{-1}$) ----					
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

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

[2] Presented by year and by all years combined despite treatment by year interaction in statistical model

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

Table 2.3. 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	5.0928	1.2935	0.7418	0.1338	-0.0075	0.0030	0.3350	0.3313
HL	11.0604	1.4940	0.5974	0.1251	-0.0042	0.0023	0.3509	0.3472
OP	8.2203	1.6432	0.8774	0.1417	-0.0111	0.0027	0.2653	0.2611

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

Table 2.4. Forage productivity, residual forage mass, and individual animal intake by treatment across three summers.

	Treatment[1]				Tukey's adjusted P-values[1]		
Year	BW	HL	OP	SE	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
	--- Intake (kg · d^{-1}) ---						
2014	1.6	1.5	1.5	0.06	0.9608	0.9571	1.0000
2015	1.0	1.0	0.8	0.06	1.0000	0.7869	0.8172
2016	1.0	1.0	0.9	0.06	1.0000	0.7673	0.6840
Average[3]	1.2	1.2	1.1	0.03	0.7989	0.0269	0.1244

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

[2] Presented by year and by all years combined despite treatment by year interaction in statistical model

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

Table 2.5. Nutritive value characteristics of mixed forage samples collected across all three summers.

	Treatment[1]				Tukey's adjusted P-values[1]		
Year	BW	HL	OP	SE	BW vs. HL	BW vs. OP	HL vs. OP
	------ N, $g \cdot kg^{-1}$ ------						
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, $g \cdot kg^{-1}$ ----						
2014	505.4	474.2	499.9	5.4	0.0024	0.9987	0.0274
2015	543.4	509.1	520.7	6.2	0.0038	0.1945	0.9217
2016	534.4	536.3	546.0	6.2	1.0000	0.9224	0.9729
Average[2]	527.7	506.5	522.2	3.4	<0.0001	0.4926	0.0042

[1] Treatment: 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 by year interaction in statistical model

Table 2.6. Nutritive value characteristics of orchardgrass samples collected across second and third summers.

	Treatment[1]				Tukey's adjusted P-values[1]		
Year	BW	HL	OP	SE	BW vs. HL	BW vs. OP	HL vs. OP
	------ N, $g \cdot kg^{-1}$ ------						
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, $g \cdot kg^{-1}$ ----						
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

[1] Treatment: 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 by year interaction in statistical model

Table 2.7. Percent cover of forages within treatments by species or groups.

	Treatment[1]				Tukey's adjusted P-values[1]		
Year	BW	HL	OP	SE	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 weed, % --					
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
		---- C4 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
	---- *Bromus* spp., % ----						
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
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

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

[2] Presented by year and by all years combined despite treatment by year interaction in statistical model

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

Table 2.8 Broadleaf species included in species composition analysis

Common name	Binomial
Stickweed	*Verbesina occidentalis*
Wild basil	*Clinopodium vulgare*
Horse nettle	*Solanum carolinense*
Milk thistle	*Silybum marianum*
Canadian thistle	*Cirsium arvense*
White campion	*Silene latifolia*
Lambs quarter	*Chenopodium album*
Fleabane	*Erigeron* spp.
Yellow woodsorrel	*Oxalis stricta*
Wood geranium	*Geranium maculatum*
Dandelion	*Taraxacum* spp.
Narrowleaf plantain	*Plantago lanceolata*
Ox eye daisy	*Leucanthemum vulgare*
Wild lettuce	*Lactuca virosa*
Marestail	*Conyza canadensis*
Common ragweed	*Ambrosia artemisiifolia*
Blue violet	*Viola sororia*
Henbit	*Lamium amplexicaule*
Chickweed	*Stellaria media*
Sulfur cinquefoil	*Potentilla recta*
Japanese honeysuckle	*Lonicera japonica*
Virginia pepperweed	*Lepidium virginicum*
Curly dock	*Rumex crispus*
Crown vetch	*Securigera varia*
Blackberry	*Rubus* spp.
Sowthistle	*Sonchus oleraceus*
Pinnate tansy mustard	*Descurainia pinnata*
Autumn olive	*Elaeagnus umbellate*
Pink deptford	*Dianthus armeria*
Poison ivy	*Toxicodendron radicans*
Multiflora rose	*Rosa multiflora*
Greater burdock	*Arcticum lappa*
Wild onion	*Allium* spp.
Common amaranth	*Amaranthus retroflexus*
Spotted knapweed	*Centaurea maculosa*
Wild carrot	*Daucus carota*
Common mullein	*Verbascum thapsus*
Deertongue	*Dichanthelium clandestinum*
Tick-trefoil	*Desmodium* spp.
Greenbrier	*Smilax* spp.

Spiny amaranth	*Amaranthus spinosus*
Purslane	*Portulaca oleracea*
Watercress	*Nasturtium officinale*
Creeping charlie	*Glechmoa hederacea*
Jimsonweed	*Datura stramonium*
Spotted spurge	*Euphorbia maculata*
Silverleaf nightshade	*Solanum elaeagnifolium*
Pokeweed	*Phytolacca americana*

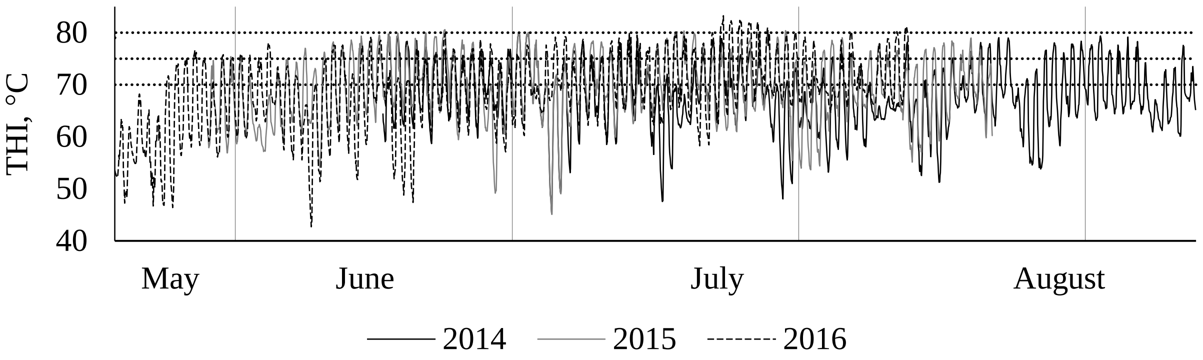


Figure 2.1. THI values as measured across the study period by year. Uncomfortable conditions = 70.0-74.9; stressful conditions = 75.0-79.9; severe heat stress > 80.0 (Silanikove, 2000).

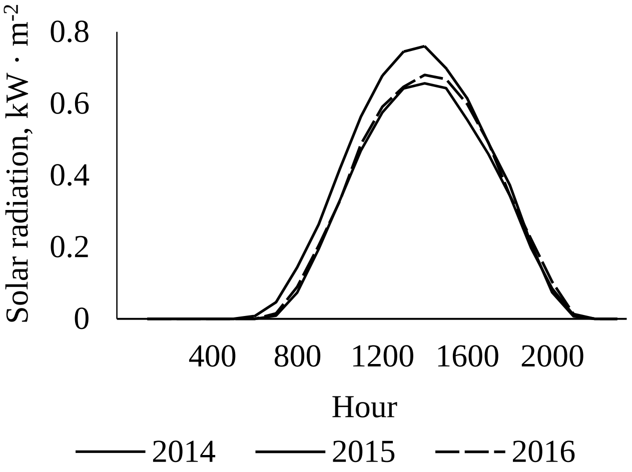


Figure 2.2. Mean solar radiation by year over a 24-hr period.

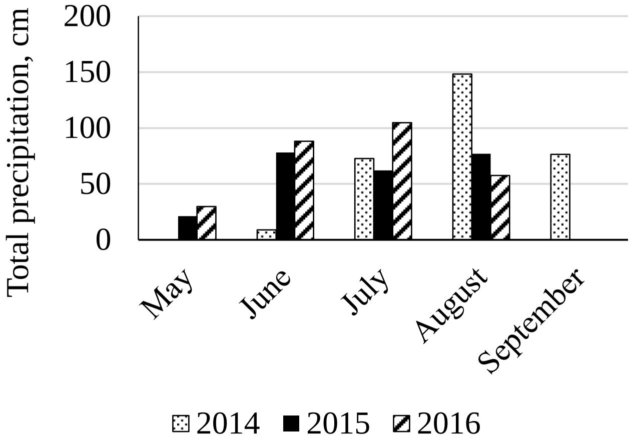


Figure 2.3. Monthly precipitation each year within the study period.

Chapter 3: Lamb behavior in hardwood silvopastures

Abstract

With no difference in animal gain between silvopastures and open pasture systems, it is evident that some other forage characteristic or animal physiological benefit compensates for lower forage productivity in some silvopastures. The purpose of the experiments detailed in this chapter was to distinguish the effects of trees in silvopastures on animal behavior, in particular the time budget of each animal in the three systems. Behavior measures were recorded within a replicate within a week, and these measures were taken sequentially within three experimental periods. Ewe lambs ($n = 3$) within each experimental unit were equipped with a wideband audio recording device to detect prehension events. Time-lapse cameras documented sheep behavior every 60 seconds. In the silvopastures, the lambs spent over 90% of daylight hours within shade boundaries. Lambs in silvopastures spent more ($P \leq 0.01$) time lying down than animals in the open pastures, while lambs in the open pastures spent more ($P < 0.0001$) than 2 hours longer each day standing. Lambs in the black walnut silvopastures spent more time grazing (488 ± 14 minutes $\cdot$ day^{-1}) than lambs in the honeylocust silvopastures (438 ± 14 minutes $\cdot$ day^{-1}; $P = 0.0493$) and lambs in the open pastures (417 ± 14 minutes $\cdot$ day^{-1}; $P = 0.0026$). There was no difference in grazing time for lambs in the latter two systems ($P = 0.5597$). Spectral analysis revealed that the lambs in the black walnut silvopastures grazed more frequently than the lambs in the other systems for both years. The acoustic analysis, although limited by recorder durability to 47 complete recordings, revealed no difference in total bites taken by lambs in the silvopastures and open pastures per day ($P \geq 0.7222$) or in the morning ($P \geq 0.2069$), afternoon ($P \geq 0.5816$), and evening periods ($P \geq 0.9337$).

Introduction

Few studies have explored how temperate silvopastures designed and managed with deciduous trees affect both the forage base and the performance and behavior of grazing ruminants. Forage production and nutritive value vary quite widely depending on tree species and management, making relationships to animal performance more difficult to determine. While deciduous silvopastures may differ from open pastures in terms of forage yield, composition, or nutritive value, these responses do not necessarily track differences in animal performance between silvopastures and open systems (Peri et al., 2001; Lehmkuhler et al., 2003; Kallenbach et al., 2006).

Recent research with lambs grazing in black walnut- and honeylocust-based silvopasture systems suggests animal performance is comparable to that from open pastures, even when forage yield is reduced (Fannon-Osborne, 2012). However, the mechanisms behind these responses have not been clearly defined. Some data suggest that increased forage nutritive value compensates for lower forage mass in silvopastures (Kallenbach et al., 2006), but lower soluble carbohydrates (Buergler et al., 2006) and only moderate, variable responses in terms of fiber digestibility (Fannon-Osborne, 2012) challenge this idea. Altered animal behaviors – such as grazing time, rumination, standing, and lying – and consequences to energy expenditure may thus be more important drivers of the similar animal gains observed between open and silvopasture systems.

Animal behavior in silvopasture has not been well studied. Heat load may change activities and intensify stresses experienced by animals in open pastures, thus increasing time and energy spent in behaviors to stabilize body temperature. Ambient temperatures are lower and less variable in silvopasture systems; thus, animals may experience more time with conditions suitable for grazing and increase dry matter intake (DMI) (Mitlohner and Laube, 2003). Distinguishing between reduced energy needed for maintenance versus greater opportunity for grazing in pasture systems is challenged by the limited tools for monitoring grazing animals, and current methods involve time-intensive observations. Novel methods for studying animal behavior in pasture systems were employed, including using time lapse cameras to document animal behavior by minute and using digital recorders to acoustically detect prehension events and grazing behavior (Clapham et al., 2011).

Materials and Methods

All procedures were approved by the Virginia Tech Institutional Animal Care and Use Committee under protocol number 14-075. Forage and livestock management practices were reported in Chapter II.

Acoustics

In 2015 and 2016, three sheep in each experimental unit (EU) within a block were fitted with a Roland R-05 recorder (Roland Corporation, Los Angeles, CA), which recorded WAV files at a 16-bit resolution and 48-kHz sampling rate, and a Sennheiser ME-2 lavalier microphone (Sennheiser Electronic Corporation, Wedemark, Germany). Recording input volume was set to 80. Data were saved to a 32-Gb 200x Platinum II SDHC Class 10 SD card (Lexar Media, Inc., Fremont, CA). Rechargeable AA batteries (Duracell, Inc., Fairfield County, CT) were used in the recorders. A large Dog Body Harness (PetSmart, Phoenix, AZ) with an Eagle Creek Pack-it Specter Quarter Cube (Eagle Creek, Carlsbad, CA) housed the recorder, which was wrapped with bubble wrap packaging. From the recorder, the microphone cord ran through 6-mm plastic tubing to a nylon adjustable Goat Halter (Weaver Leather, LLC., Mount Hope, OH) where the microphone was secured with electrical tape near the mouth of the lamb.

Recording files were automatically split after reaching 2-Gb in size. Recorders were usually placed on the animals before 700 h. Recorders were removed from the animals after 2100 h both years, except in the case of rain in 2016. The devices remained on nine animals for one day before being transferred to sheep in another block the following week for three consecutive weeks of measures in each 4-week period.

Recordings were manually analyzed for validity, primarily ensured by having a secure microphone connection. Only sets with all valid recordings were analyzed further. Valid recordings were reduced to monaural recordings and processed with a high-pass frequency filter (600-Hz, 4800-dB) in Audacity v. 2.0.6 (Audacity Team). A 10-second segment of grazing time was selected from each valid recording and the bites therein were manually counted using Audacity 2.0.6 software. Any recording that was too loud or too quiet, based on the determined average threshold of all the recordings, was excluded from the analysis. In SIGNAL and GRASS software (Engineering Design, Berkeley, CA), the selected clip was analyzed for necessary parameters to include all identified bites and exclude all extraneous noise as described in Clapham et al. (2011). The necessary parameters included low and high frequency cutoffs, envelope decay time, detection threshold, minimum event gap, minimum pulse length, minimum and maximum event lengths, and pre- and post-event time extensions. That same segment was then analyzed automatically with those defined parameters using SIGNAL/GRASS detection software and the results were compared to the manual bite count in Microsoft Excel v. 2013 (Microsoft Corporation, Redmond, WA). Finally, after post-processing the entire recording in Audacity v. 2.0.6, prehension events in the entire recordings were detected by SIGNAL/GRASS software. The output recorded each bite event with a start and stop time stamp, along with the voltage of the signal. Data included in the analysis were collected between 700 h and 2100 h.

Time Lapse Cameras

Time-lapse imagery was collected during the same time as the acoustic recordings. Moultrie D-500 trail cameras (EBSCO Industries, Inc., Birmingham, AL) were set to visually encompass the entire subpaddock containing the lambs with recorders, capturing images every 60 seconds. Prior to sampling, the sheep of interest were marked with pink, orange, or blue fluorescent spray paint to distinguish sheep within the same EU.

The photos were processed sequentially by manually recording the behavior (standing up, lying down, grazing, drinking water, eating mineral) and shade utilization (in the shade, in direct sunlight, overcast or low sun angle) of each sheep by minute. Data included in the analysis were collected between 830 h and 2030 h in 2015, while data included in 2016 were collected between 715 h and 2045 h. Total time in each behavior was calculated by the summation of total minutes engaged in a given behavior. Shade use was calculated by the summation of total minutes in shade and the minutes of time during which the sky was overcast.

The proportion of animals in an EU that were grazing each minute was summarized and plotted in Microsoft Excel v. 2013.

Spectral analysis of grazing behavior was completed to determine the grazing cycles of the lambs in the systems each year, as described in Fuller (1976) and Diggle (1990). In spectral analysis, the total variation in a time series is partitioned into sums of squares at each Fourier frequency, or $\omega = 2\pi/n$ where n is the total number of observations in the series. At each Fourier frequency, a sum of squares, or ordinate, is calculated using the equation

$$\mathrm{I}(\omega)=\mathrm{n}^{-1}\left[\left\{\sum_{t=1}^{n} y_t\cos(\omega t)\right\}+\left\{\sum_{t=1}^{n} y_t\sin(\omega t)\right\}\right]$$

where $I(\omega)$ is the Fourier ordinate calculated at each frequency (ω), n is the number of observations in the series, and t is the time in minutes. The spectrum for each lamb and grazing day combination was computed using PROC SPECTRA in SAS 9.4 (SAS Inst., Cary, NC). The ordinates of lambs in a single treatment were averaged to create a composite ordinate at each Fourier frequency using

$$\bar{I}(\omega_j)=\frac{1}{r}\sum_{k=1}^{r} I_k(\omega_j)$$

where r is the number of lamb and day combinations sampled for each treatment, and $I_k(\omega_j)$ is the ordinate of the *k*th series at frequency $\omega = 2\pi/n$. An F test was used to identify ordinates that have a significant effect versus ordinates that are merely white-noise (Fuller, 1976).

The average spectrum of two treatments can be compared using the procedure described in Diggle (1990). The ratio of two spectra is computed by

$$R(\omega)=\frac{\bar{I}_1(\omega)}{\bar{I}_2(\omega)}$$

with an F distribution of $2r_1$, $2r_2$ df. The ordinates were averaged and the ratios of these ordinates at each Fourier frequency for each treatment combination were calculated in Microsoft Excel v. 2013. The average ordinates were plotted against period along with the Fisher Kappa test critical value. The ratios of these ordinates were plotted against period along with the 5% and 95% critical values for each treatment combination.

Statistical Analysis

For the analysis of the acoustic data, a mixed ANOVA of daily bite count and bite count in morning, afternoon, and evening periods between treatments was analyzed with PROC MIXED in SAS Studio, v. 3.5 (SAS Inst., Cary, NC). Morning was defined as 700 to 1100 h, afternoon was defined as 1101 to 1600 h, and evening was defined as 1601 to 2100 h. Experimental design was treated as a randomized complete block design with three replications.

LS-means and Tukey's adjusted differences were calculated for each year and treatment combination. Differences were considered significant when $P < 0.05$ and trends when $P < 0.10$.

For the analysis of the time-lapse imagery data, a mixed ANOVA of time spent lying down, grazing, standing up, and time in the shade between treatments was analyzed with PROC MIXED in SAS Studio, v. 3.5 (SAS Inst., Cary, NC). Experimental design was treated as a randomized complete block design with three replications and a repeated measures analysis of variance by month. Year was included as a random effect. LS-means and Tukey's adjusted differences were calculated for each year and treatment combination. Differences were considered significant when $P < 0.05$ and trends when $P < 0.10$.

Results

Acoustics

The parameters defining an intake event were slightly different than those established in Clapham et al. (2011). Although the physical characteristics of the acoustic signal of a prehension event remained the same, including the low and high frequency cutoffs and the detection threshold, most of the parameters related to the timing of the signals were adjusted to correct for the faster grazing behavior of lambs compared to cows (Table 3.1). These parameters included envelope decay time, minimum event gap, minimum and maximum event lengths, and pre- and post-event time extensions. Other timing parameters not adjusted include the minimum pulse length.

Of the 162 recordings attempted throughout the two years, 47 recordings were valid and complete enough to include in the analysis. The comparison of manually counting prehension events to the automatic detection of prehension events using SIGNAL/GRASS in a short segment from each valid and complete recording is shown in Fig. 3.1. The R^2 of the line was 0.9697. The equation of the line was

$$\text{Automatic event count}=[1.05\times(\text{Manual event count})]-0.33$$

Of the 47 valid recordings, there were no differences in daily bite count for the lambs in the different systems (Table 3.2).

Figure 3.2 presents the grazing behavior of three lambs, one from each treatment in the first block, from July 25, 2016. The sheep had been moved to a fresh subpaddock on July 23, 2016.

Time Lapse Cameras

In 2015, a total of 22, 22, and 26 lamb and grazing day combinations were recorded and analyzed with the trail cameras in the black walnut silvopastures, the honeylocust silvopastures, and the open pastures, respectively. In 2016, a total of 27, 24, and 27 lamb and grazing day combinations were recorded and analyzed in the black walnut silvopastures, the honeylocust silvopastures, and the open pastures, respectively.

Lambs in the silvopastures actively followed the shade from the trees, spending over 90% of the day within shade boundaries (Table 3.3). Lambs in the open pastures spent significantly less time within shade than the lambs in the silvopastures. The lambs in the open pastures had partial access to shade in the mornings or evening hours when trees within the silvopastures or surrounding woodlots and riparian areas blocked the sun at low angles. Shade use, including minutes when an overcast sky made shade from the tree negligible, was higher for all treatments in 2016 due to a greater number of overcast minutes. The average number of overcast minutes in 2015 was 167 minutes per day, while the average for 2016 was 259 minutes per day. This discrepancy was likely the cause of the treatment by year interaction found in the statistical model for shade use (P = 0.0011).

The lambs in the silvopastures spent more time lying down than lambs in the open pastures in 2015, but not 2016. For both years, however, lambs in the open pastures spent more time standing up than lambs in the silvopastures, though the time spent standing was greater in 2015 than in 2016 for lambs in all treatments, particularly the lambs in the open pastures.

Lambs in the black walnut silvopastures spent the most time grazing. Lambs in the honeylocust silvopastures spent as much time grazing as the lambs in the open pastures.

The proportion of total animals grazing by minute in 2015 is shown in Fig. 3.3. In 2015, the lambs in silvopastures grazed more evenly than lambs in the open pastures, though the largest grazing bout occurred in the evening for all animals. The lambs in the open pastures appeared to graze less in the middle of the day than the lambs in the silvopastures, particularly than the lambs in the black walnut silvopastures. The evening grazing bout started at a later time in the afternoon for lambs in the open pastures compared to lambs in the silvopastures. The lambs in the open pastures also had a dominant grazing bout in the morning, which was not as evident for lambs in the silvopastures.

The proportion of total animals grazing by minute in 2016 is shown in Fig. 3.4. In 2016, the lambs in the black walnut silvopastures grazed more evenly throughout the day than lambs in the other systems. Lambs in the black walnut silvopastures had four dominant grazing bouts, including one in the morning, one in the early afternoon, one in the late afternoon, and the largest grazing bout in the early evening. Lambs in the honeylocust silvopastures appeared to graze throughout the day, but most of the time spent grazing by these lambs occurred in the final grazing bout. Lambs in the open pastures appeared to have more distinct grazing bouts than the lambs in the other systems, with a grazing bout in the morning, two grazing bouts in the afternoon, and a final evening grazing bout that started later than the final grazing bout for the lambs in the silvopastures. The grazing behavior of the lambs appeared to vary by year.

The composite periodograms of lamb grazing behavior by treatment in 2015 and 2016 with the F critical value (8.776 and 8.901, respectively) are plotted in Fig. 3.5. In 2015, the lambs in the honeylocust silvopastures displayed significant ordinates at frequencies of 90.125, 120.167, 144.2, 180.25, and 240.333. The lambs in the black walnut silvopasture had similar significant ordinates with the exception of the ordinate at frequency 90.125. The lambs in the open pastures had significant ordinates only at the frequencies 180.25 and 240.333. In 2016, the lambs in the open pastures had significant ordinates at frequencies 115.857, 135.167, 162.2, 202.75, and 270.333. The lambs in the black walnut silvopastures were similar, but did not display significant ordinates at frequencies 115.857 and 270.333. The lambs in the honeylocust silvopastures were also similar, but did not display significant ordinates at frequency 162.2.

The ratios of the ordinates for the different treatments in 2015 with the 5% and 95% critical limits are plotted in Fig. 3.6. Lambs in the black walnut silvopastures grazed more frequently than lambs in either other treatment with significantly large ordinate ratios at the early frequencies. The ordinate at the frequency, 120.167, was also significantly larger for the lambs in the black walnut silvopastures compared to the lambs in the open pastures. A similar phenomenon was noticed for the lambs in the honeylocust silvopasture at early frequencies and the frequency, 90.125.

The ratios of the ordinates for the different treatments in 2016 with the 5% and 95% critical limits are plotted in Fig. 3.7. Lambs in the black walnut silvopastures again grazed more frequently than lambs in either other treatment. During this year, however, the lambs in the open pastures grazed slightly more frequently than the lambs in the honeylocust silvopastures.

Discussion

Acoustics

Although the parameters for defining an intake event in the GRASS/SIGNAL software varied from those utilized by Clapham et al. (2011), this was the case both to take into account the more intense biting rate of sheep (Orr et al., 1997) compared to cattle (Erlinger et al., 1990) and because more bite events were accurately detected with these changes. Biting rates were similar in this study to other estimates of biting rates in sheep (Champion et al., 1994; Orr et al., 1997). The correlation between manually comparing bite counts in a recording to the automatic detection of bites in a recording indicates the high level of accuracy of this method for detecting the grazing activity of sheep. The challenge faced throughout the study remained in keeping the recorders running and minimizing the variability between recordings, including distance to noise source and device settings and functions.

There were no differences detected between treatments in total bites taken per period of the day and for the entire day, and this was largely a function of the variability between measurements. Fasting – or time since the last rotation in a rotational stocking system – is a major driver of grazing time in ruminants (Newman et al., 1994), and it seems that this effect precluded our ability to detect differences between treatments in addition to the low number of complete recordings included in the final analysis.

From this limited analysis, however, it appears that the presence of trees does not inhibit grazing. Some studies indicate that dairy cattle, by seeking artificial shade, might suffer reduced intake levels during the day (Kendall et al., 2006). In silvopastures, where shade is evenly distributed throughout the pasture along with adequate forage for intake, grazing time has, in some cases, been found to be greater than in open pastures (Karki and Goodman, 2010).

Time Lapse Cameras

The lambs in the silvopastures actively followed the shade of the trees as the sun moved throughout the day, spending over 90% of daylight hours within the boundaries of the shade. This study substantiates the already overwhelming evidence that livestock, including sheep and cattle, prefer shade and will actively seek it in order to minimize heat stress (Roman-Ponce et al., 1977; Morrison, 1983; Bennet et al., 1985; Johnson, 1987; Blackshaw and Blackshaw, 1994). Shade use increased for lambs in all treatments during 2016, though this was primarily driven by an increased number of overcast days during the third summer. The preference that dairy cattle exhibit for shade increases with rising temperatures and shade availability (Kendall et al., 2006; Tucker et al., 2008; Schütz et al., 2014). This study and others have demonstrated that silvopastures can increase site utilization by livestock while evenly distributing urine and manure (Karki and Goodman, 2010) by taking advantage of the shade preference of livestock and through an even distribution of shade across the landscape.

Preference alone, however, does not indicate greater levels of animal welfare (Broom, 1988).

The lambs in the silvopastures also spent more time lying down than the lambs in the open pastures. Time spent lying down is a traditional metric of animal comfort (Haley et al., 2000; Winckler et al., 2003). In addition, conductive heat loss with the ground is only an effective means of cooling if the ground is cooler than the body of the lamb. As might be expected, soil surface temperatures are generally lower in silvopastures and greater in open pastures (Buergler et al., 2006). As a result, ground within the silvopastures provides a more effective means of conductive heat loss than ground in the open pastures.

Conversely, the lambs in the open pastures spent more time standing up than the lambs in the silvopastures. Standing up is a general response of livestock to heat stress (Cook et al., 2007; Scaglia and Boland, 2014). Greater time spent standing indicates the level of heat stress experienced by the lambs in the open pastures as they sought to increase the effectiveness of convective heat loss through improved air flow (Silanikove, 2000).

Cattle that graze toxic endophyte (*Epichloë coenophialum)* infected tall fescue (*Schedonorus arundinaceous*) pastures, have increased susceptibility to heat stress and spend less time grazing and lying down and more time standing up compared to cattle grazing non-toxic tall fescue (Coffey et al., 1992; Seman et al., 1997). This present study compared only wild type, presumably toxic, endophyte-infected tall fescue across treatments. It remains to be seen how trees in non-toxic endophyte infected tall fescue pastures affect animal behavior and performance.

It is interesting to note that while all animals spent less time standing up in 2016 compared to 2015, this diifference was particularly evident for the lambs in the open pastures. The lambs in the open pastures also spent more time lying down in 2016, while the lambs in the silvopastures spent less time lying down that same year compared to 2015. This phenomenon occurred despite more moderate THI conditions in 2015 than in 2016. The likely reason for this phenomenon was that a hair sheep breed was used the third year. Hair sheep are generally more heat tolerant than wool sheep because wool impairs the effectiveness of sweating as a means of evaporative cooling (Marai et al., 2007). This effect was also evident in the live weight gains of the animals. The difference in ADG of the lambs in the silvopastures compared to those of the lambs in the open pastures was greater in 2015 than in 2016 (Chapter II).

Taken alone, preference for shade, time spent resting, or time spent standing, do not indicate good animal welfare (Broom, 1988), but while understanding that these responses were coupled with hot environmental conditions, it can be concluded that the animals in the silvopastures were more comfortable (Silanikove, 2000).

The lambs in the black walnut silvopastures spent more time grazing, though this is merely a rough estimate of grazing time and was hindered by both obscurity of the field of view within the photos and the challenge of differentiating grazing time from time spent standing. The potential inaccuracies in documenting grazing time from still photos is evident in Fig. 2. From the figures it is clear that at some points in time, the acoustic analysis and time-lapse imagery analysis do not always concur. In addition, grazing time does not necessarily reflect intake, which is dependent, not just on grazing time and grazing intensity, but also on bite size. Nevertheless, the greater time spent grazing by lambs in the black walnut silvopastures is plausible, though it is not clear whether this is a function of more comfortable conditions, as has been demonstrated in feedlots where nutrition is not limiting (Mitlohner et al., 2001; Gaughan et al., 2010; Blaine and Nsahlai, 2011), or a lower forage sward height and mass, which would require more time spent grazing to compensate for reduced bite size (Allden and McDWhittaker, 1970; Karki and Goodman, 2010). Where forage sward conditions were more similar to those of the open pastures, the lambs in the lighter shade of the honeylocust silvopastures spent the same amount of time grazing as the lambs in the open pastures. When shade is provided apart from feed, as in the case of shade structures provided away from pastures, dairy cattle will spend the majority of the daylight hours in the shade which will negatively affect their daytime grazing behavior (Kendall et al., 2006). Such phenomenon would not be expected in silvopastures, where feed and shade are available in the same locales.

Significantly large ordinates occurred for lambs in all treatments at frequencies of around 2 to 3 hours, indicating the shorter grazing cycles displayed by lambs compared to cattle (Seman et al., 1997). Others have observed, however, that the grazing cycles of sheep followed 8 hour cycle lengths (Champion et al., 1994). The data presented in the current study only includes daytime data, which may account for this discrepancy. Eight is a harmonic of a 24 hour day. In addition, the present study utilized rotational stocking management, while Champion et al. (1994) utilized continuous stocking management with a relatively even forage sward height.

Lambs in the black walnut silvopastures grazed more frequently than lambs in either of the other treatments in both years. Intake reduction is a general response of heat stressed animals, both indirectly through a reduction in passage rate and directly through an appetite-suppressing elevation of body temperatures (Silanikove, 1992; Blackshaw and Blackshaw, 1994). The lambs in the black walnut silvopastures also grazed more evenly throughout the day than lambs in the open pastures. Lambs in open pastures grazed most during the cooler evening hours and generally delayed the final grazing bout relative to the lambs in the silvopastures. On a diurnal scale, seeking shade and minimizing intake during the hottest times of the day has been understood as an adaptive mechanism for maintaining adequate levels of feed intake during periods of heat stress (Silanikove, 1992). All animals appeared to graze the most during the evening grazing bout, a pattern of activity that has been well established in grazing ruminants (Orr et al., 1997; Gregorini et al., 2006). This pattern has been explained as a mechanism for maximizing energy intake, as forage carbohydrate levels increase during the day and decrease during the night. However, the importance of minimizing activity and intake during periods of heat stress may have been underestimated or even ignored in determining the reasons for these diurnal cycles.

Lambs in the honeylocust silvopasture grazed less frequently than lambs in the open pastures in 2016. The switch to a more heat tolerant sheep breed was a likely reason that the lambs in the open pastures displayed behavior less indicative of heat-stressed animals than in the previous year.

Conclusion

The methods used for determining lamb grazing behavior were well-correlated, but the analysis of time lapse imagery permitted a more complete analysis of daily time budgets than the acoustic analysis. This was due both to the additional information provided by the time lapse imagery on time spent in the shade, standing, and lying down, along with the low number of complete audio recordings that were collected. From the acoustic analysis, no differences were found in daily bite counts and bite count by time of day for the lambs. From the analysis of the time lapse imagery, it was found that the lambs preferred shade and actively sought it throughout the day. Lambs in silvopastures were more comfortable, spending more time lying down and less time standing up, than lambs in open pastures. Lambs in the silvopastures grazed more frequently and more evenly throughout the midday hours compared to the lambs in the open systems, except in the final year when a hair sheep breed was used. This indicates that ambient conditions in the silvopastures were more favorable for grazing than in the open pastures, but that an increased heat tolerance of the lambs may minimize the difference in grazing behavior between lambs in silvopastures and open pastures.

Table 3.1. Parameters for defining an intake event in GRASS/SIGNAL software.

Parameter	Measurement
Low frequency cutoff (kHz)	17
High frequency cutoff (kHz)	None
Envelope decay time (ms)	50
Detection threshold (V)	0.013
Minimum event gap (ms)	40
Minimum pulse length (ms)	1
Minimum event length (ms)	50
Maximum event length (ms)	200
Pre-event time extension (ms)	10
Post-event time extension (ms)	10

Table 3.2. Acoustic analysis of bite counts within periods of day and entire day.

	Treatment[1]			Tukey's adjusted P-values[1]		
Year	BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
	---- Morning ± SE (bites) ----					
2015	1333 ± 1112	677 ± 1492	3341 ± 1316	0.9992	0.8494	0.7613
2016	3659 ± 1123	1451 ± 1047	2937 ± 786	0.7042	0.9946	0.8625
Average[2]	2496 ± 790	1064 ± 911	3139 ± 766	0.4700	0.8297	0.2069
	---- Afternoon ± SE (bites) ----					
2015	4771 ± 1588	4849 ± 2131	3712 ± 1879	1.0000	0.9979	0.9985
2016	7133 ± 1604	5136 ± 1495	7518 ± 1123	0.9405	1.0000	0.7962
Average[2]	5952 ± 1129	4992 ± 1301	5615 ± 1095	0.8436	0.9750	0.9289
	---- Evening ± SE (bites) ----					
2015	9747 ± 1965	9925 ± 2636	9018 ± 2325	1.0000	0.9999	0.9998
2016	12072 ± 1984	10874 ± 1849	13267 ± 1389	0.9976	0.9960	0.9022
Average[2]	10910 ± 1396	10399 ± 1610	11142 ± 1354	0.9689	0.9921	0.9337
	----- Daytime ± SE (bites) -----					
2015	15852 ± 4157	15451 ± 5577	16070 ± 4919	1.0000	1.0000	1.0000
2016	22865 ± 4198	17460 ± 3912	23722 ± 2939	0.9321	1.0000	0.7933
Average[2]	19358 ± 2954	16455 ± 3406	19896 ± 2865	0.7973	0.9906	0.7222

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

[2] Presented by year and by all years combined because of no treatment by year interaction in statistical model

Table 3.3. Time lapse imagery analysis of behavior and time in shade.

	Treatment[1]			Tukey's adjusted P-values[1]		
Year	BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
	--- Shade use ± SE (minutes) ---					
2015	655 ± 9	681 ± 9	166 ± 5	0.3093	<0.0001	<0.0001
2016	756 ± 5	748 ± 8	216 ± 5	0.9636	<0.0001	<0.0001
Average[2]	705 ± 5	715 ± 6	191 ± 4	0.4653	<0.0001	<0.0001
	----- Lying ± SE (minutes) -----					
2015	307 ± 24	333 ± 23	162 ± 22	0.9669	0.0010	<0.0001
2016	189 ± 22	254 ± 23	198 ± 22	0.3330	0.9998	0.4863
Average[2]	248 ± 16	294 ± 16	180 ± 16	0.1290	0.0118	<0.0001
	---- Standing ± SE (minutes) ----					
2015	36 ± 12	43 ± 11	252 ± 10	0.9983	<0.0001	<0.0001
2016	20 ± 9	24 ± 11	80 ± 9	0.9997	0.0009	0.0052
Average[2]	28 ± 8	33 ± 8	166 ± 7	0.8712	<0.0001	<0.0001
	---- Grazing ± SE (minutes) ----					
2015	376 ± 22	343 ± 21	304 ± 19	0.8930	0.1610	0.7423
2016	601 ± 19	532 ± 21	530 ± 19	0.1617	0.1122	1.0000
Average[3]	488 ± 14	438 ± 15	417 ± 14	0.0493	0.0026	0.5597

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

[2] Presented by year and by all years combined despite treatment by year interaction in statistical model

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

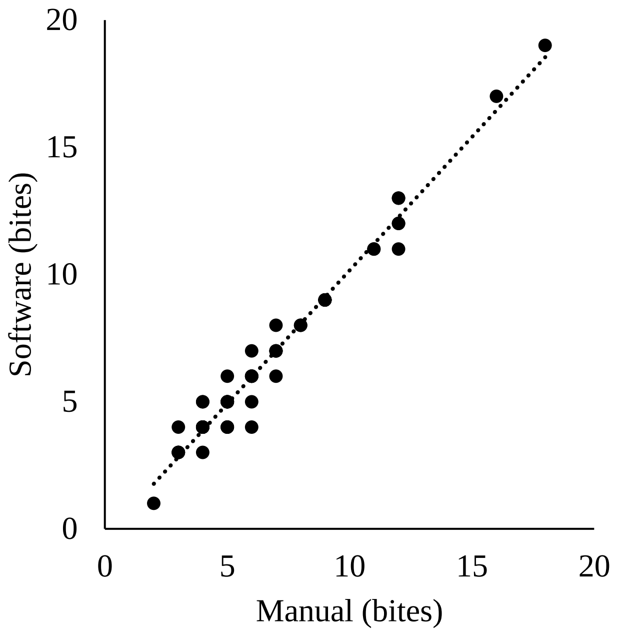


Figure 3.1. Comparison of manual estimation of bites to automatic detection of bites with SIGNAL/GRASS software from 47 ten-second recordings.

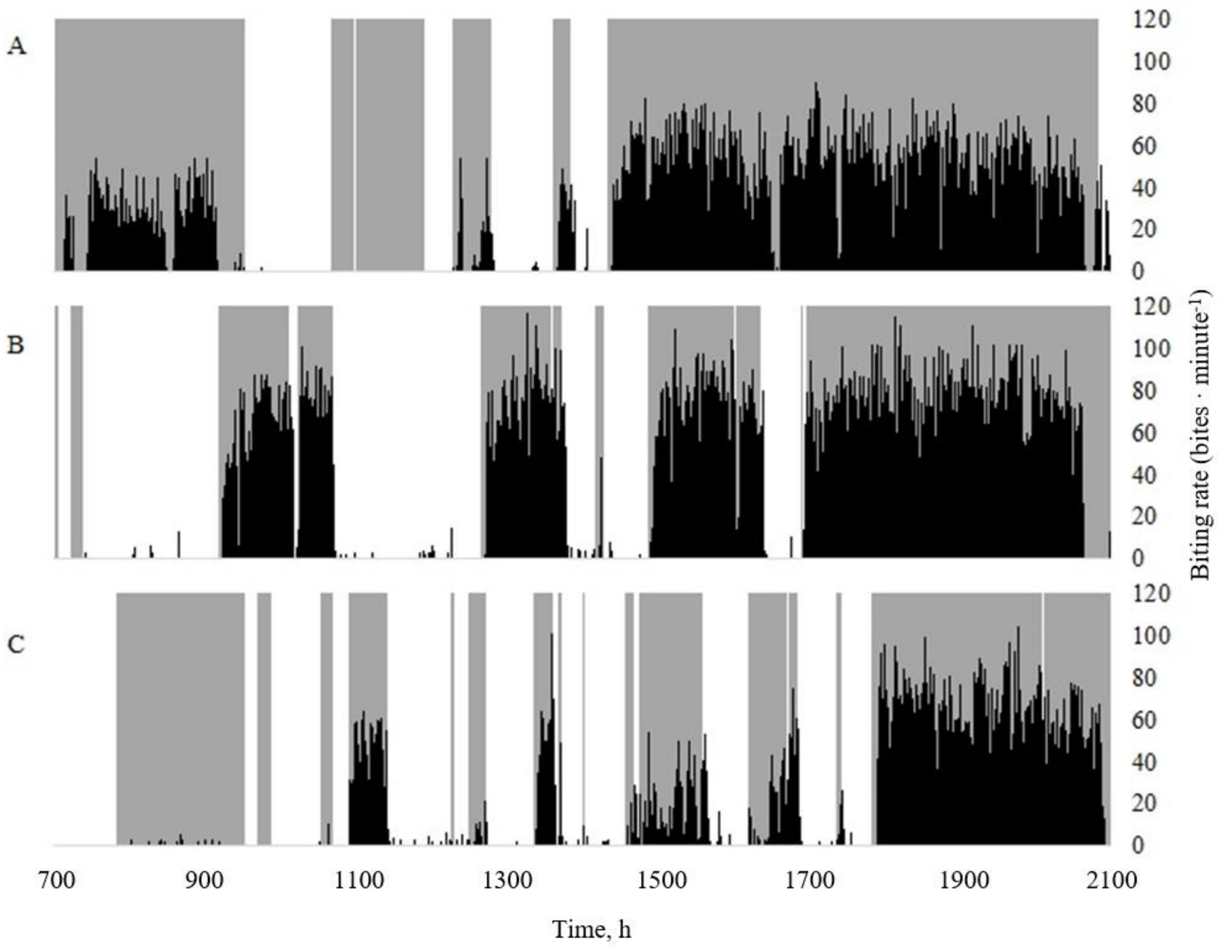


Figure 3.2. Grazing behavior of three lambs from July 25, 2016. The shaded grey lines indicate time spent grazing as estimated from the time lapse imagery. The black lines, defined by the right hand vertical axis, indicates biting rate as detected from SIGNAL/GRASS software. Time of day is defined by the horizontal axis. A) Ewe # 4985 in the black walnut silvopastures. B) Ewe #4937 in the honeylocust silvopastures. C) Ewe #4963 in the open pasture.

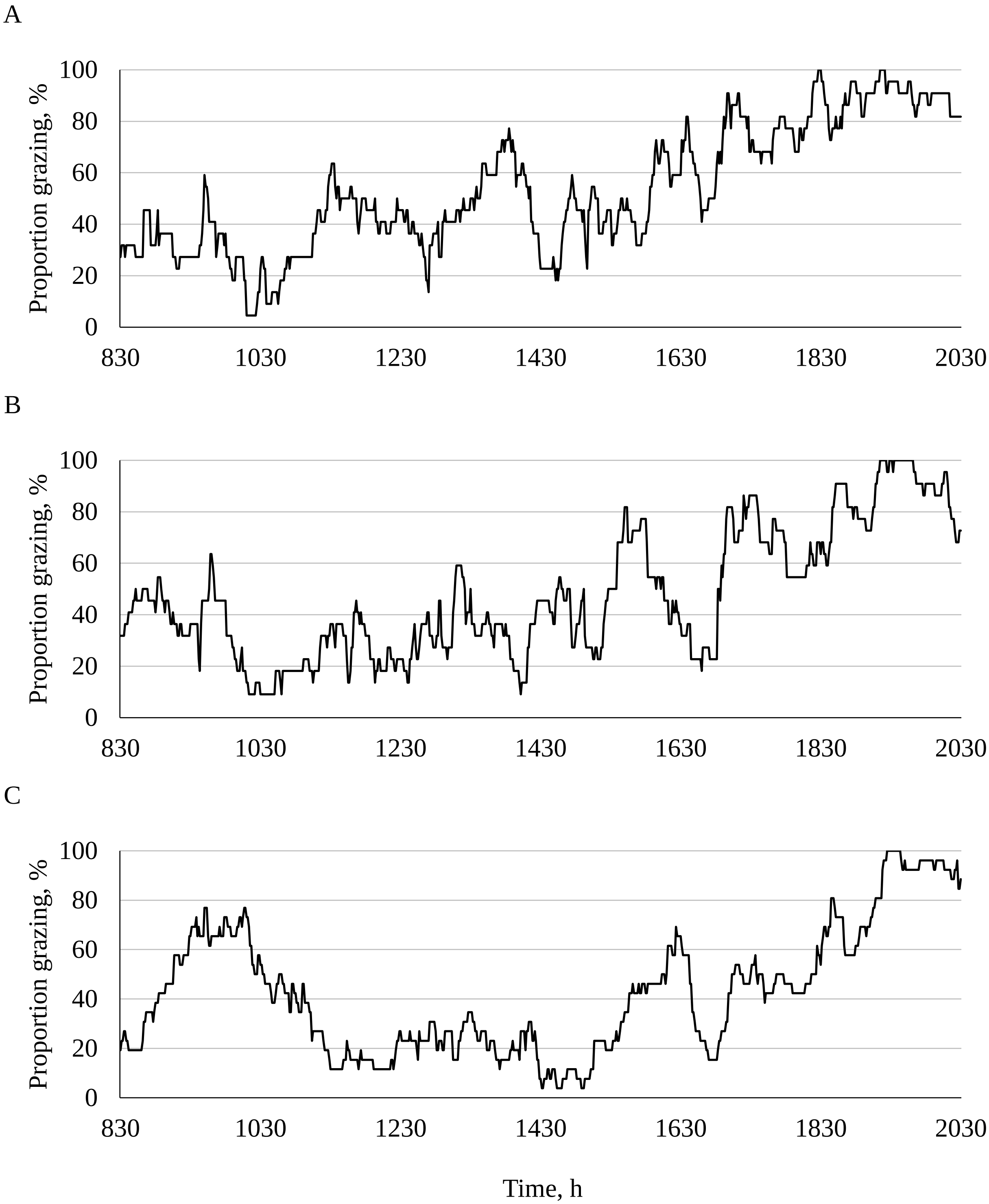
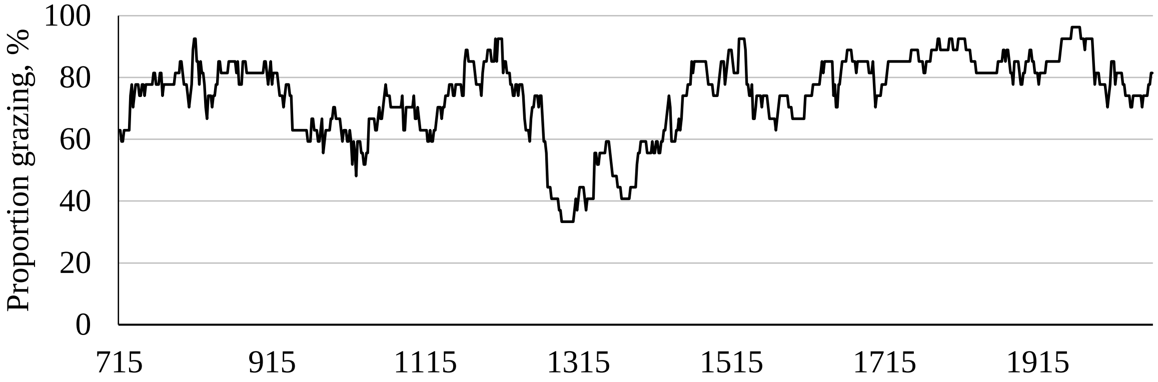
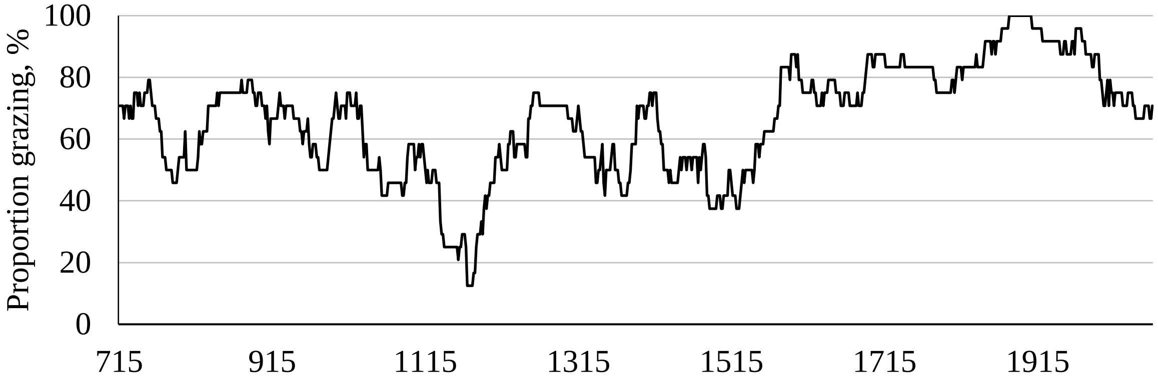

A
Proportion grazing, %
0
20
40
60
80
100
830
1030
1230
1430
1630
1830
2030
B
Proportion grazing, %
0
20
40
60
80
100
830
1030
1230
1430
1630
1830
2030
C
Proportion grazing, %
0
20
40
60
80
100
830
1030
1230
1430
1630
1830
2030
Time, h

Figure 3.3. Proportion of all animals grazing each in the black walnut silvopasture (A), the honeylocust silvopasture (B), and the open pasture (C) in 2015 from the analysis of the time lapse imagery.

A


Proportion grazing, %
100
80
60
40
20
0
715
915
1115
1315
1515
1715
1915

B


Proportion grazing, %
100
80
60
40
20
0
715
915
1115
1315
1515
1715
1915

C

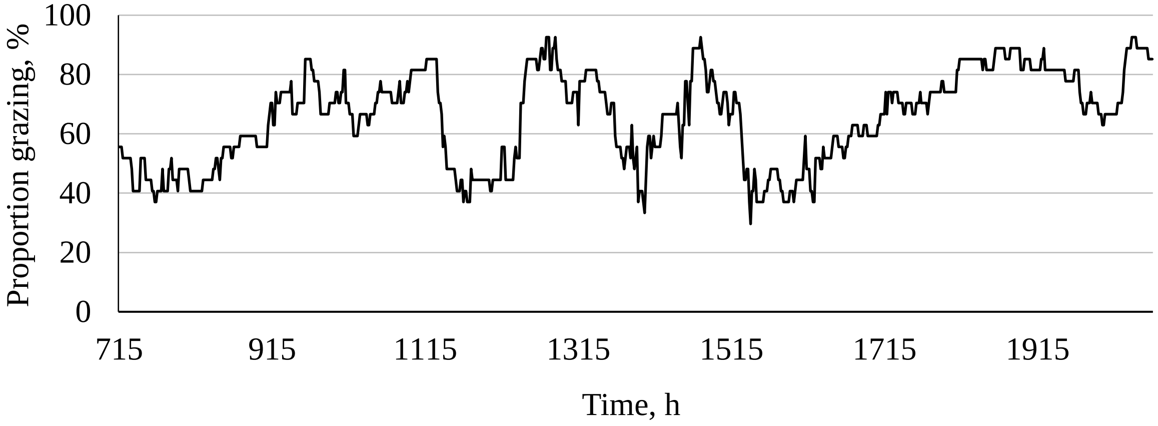

Proportion grazing, %
100
80
60
40
20
0
715
915
1115
1315
1515
1715
1915
Time, h

Figure 3.4. Proportion of all animals grazing each in the black walnut silvopasture (A), the honeylocust silvopasture (B), and the open pasture (C) in 2016 from the analysis of the time lapse imagery.

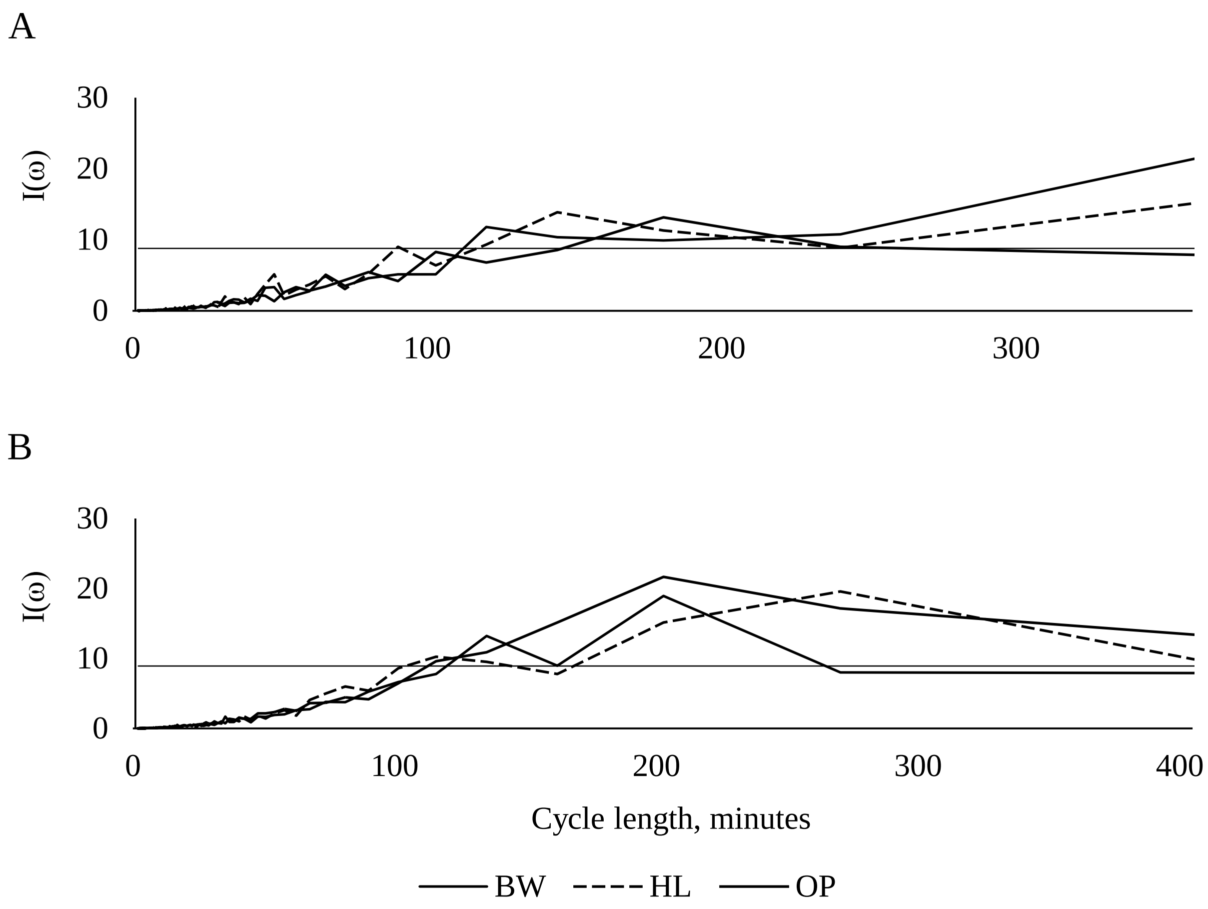


Figure 3.5. Periodogram ordinates at each Fourier frequency cycle length in 2015 (A) and 2016 (B) from the analysis of the time lapse imagery. The F critical value ($P < 0.05$) is denoted by the horizontal line. Ordinates exceeding this critical value indicate Fourier frequencies that significantly contribute to grazing cyclicity. BW = black walnut silvopastures, HL = honeylocust silvopastures, OP = open pasture.

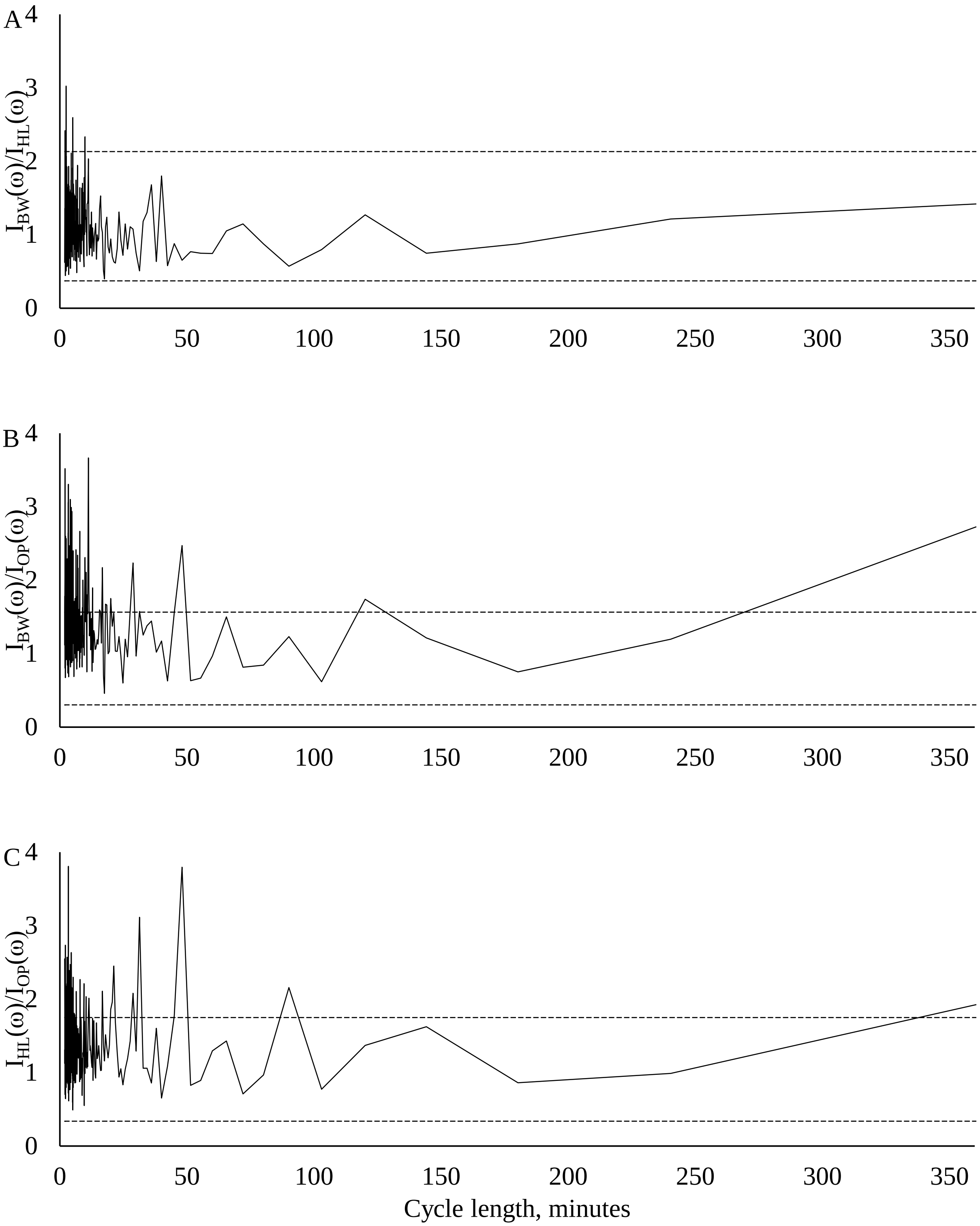

A
B
C
4
3
2
1
0
$I_{BW}(\omega)/I_{HL}(\omega)$
$I_{BW}(\omega)/I_{OP}(\omega)$
$I_{HL}(\omega)/I_{OP}(\omega)$
0
50
100
150
200
250
300
350
Cycle length, minutes

Figure 3.6. Plots of ordinate ratios at each Fourier frequency cycle length in 2015 from the analysis of time lapse imagery. The upper and lower F critical boundaries ($P < 0.05$) are denoted by the dashed horizontal lines. Ordinate ratios falling outside these boundaries indicate Fourier frequencies where the two spectra are significantly different. A) Ratio of black walnut silvopasture ordinates to honeylocust silvopasture ordinates. B) Ratio of black walnut silvopasture ordinates to open pasture ordinates. C) Ratio of honeylocust silvopasture ordinates to open pasture ordinates.

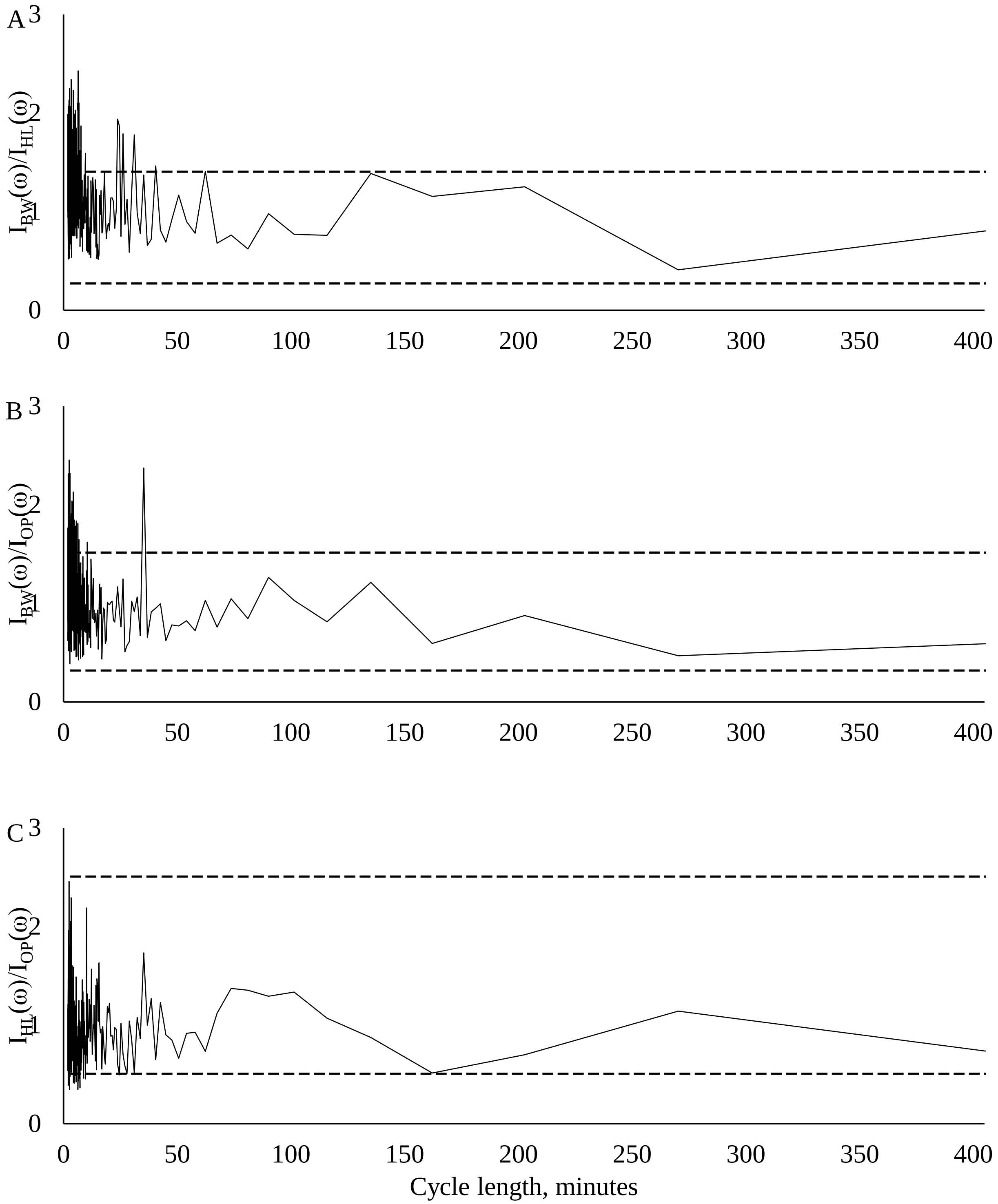

A
B
C
3
2
1
0
$I_{BW}(\omega)/I_{HL}(\omega)$
$I_{BW}(\omega)/I_{OP}(\omega)$
$I_{HL}(\omega)/I_{OP}(\omega)$
0
50
100
150
200
250
300
350
400
Cycle length, minutes

Figure 3.7. Plots of ordinate ratios at each Fourier frequency cycle length in 2016 from the analysis of time lapse imagery. The upper and lower F critical boundaries ($P < 0.05$) are denoted by the dashed horizontal lines. Ordinate ratios falling outside these boundaries indicate Fourier frequencies where the two spectra are significantly different. A) Ratio of black walnut silvopasture ordinates to honeylocust silvopasture ordinates. B) Ratio of black walnut silvopasture ordinates to open pasture ordinates. C) Ratio of honeylocust ordinates to open pasture ordinates.

Chapter 4: Ewe lamb vaginal temperatures in hardwood silvopastures

Abstract

Shade for livestock during periods of heat stress is likely to be one of the biggest drivers for silvopasture adoption for livestock producers, yet the actual physiological benefit for animals in silvopastures is not well known. The greatest challenge in assessing heat stress and body temperatures in animals on pasture is in collecting the data with minimal disturbance. In this study, intravaginal temperature sensors were constructed from blank controlled internal drug release (CIDR) devices and small temperature loggers. Body temperatures of ewe lambs ($n = 9$) were recorded within a replicate within a week, and these measures were taken sequentially within three experimental periods. During the hottest part of the day (1300 – 1700 h), ewes in the open pasture had hotter vaginal temperatures than ewes in the black walnut silvopastures ($P \leq 0.0202$). Ewes in the open pasture experienced more fluctuation in day to nighttime core temperature change ($P < 0.0001$). Lambs in the honeylocust silvopastures displayed increasing vaginal temperatures each month, perhaps due to the declining shade cover provided by these trees over the growing season or due to more nutritious forage consumption by the lambs in these systems.

Introduction

Silvopastures provide an opportunity to manage livestock in an ecologically and economically sustainable manner, while at the same time providing livestock with a comfortable habitat. Some have posited that such environments optimize the health and well-being of livestock, and thus their productivity (Sharrow, 2000). While it is clear that silvopastures produce equivalent animal output compared to open pastures (Peri et al., 2001; Lehmkuhler et al., 2003; Kallenbach et al., 2006; Fannon-Osborne, 2012), no data are available on the actual benefit of the shade provided by silvopastures in terms of alterations to body temperatures of the animals grazing in these systems.

It should not be concluded that shade is unnecessary to animal well-being because shaded livestock have comparable rates of growth to unshaded livestock. Ruminants have a capacity for compensatory gains after periods of heat stress and low growth rates (Morrison, 1983). In addition, the capacity for measuring weight gain changes is often limited by the large fluctuation in live weights at any given moment due to the large capacity of the rumen (Bath et al., 1966; Owens et al., 1993). Thus, while an animal may be experiencing heat stress, the negative effects of that stress on the animal may not be noticed solely through a limited analysis of live weight gains, which in some cases, is measured a couple of weeks after conditions of heat stress may have occurred.

The Thermoneutral Zone (TNZ) concept for livestock is used to understand the relationship of livestock with their environment and to define the point at which ambient conditions become detrimental to animal health and well-being. (Silanikove, 2000). Schematically, the TNZ is bounded by lower and upper critical temperatures points. The lower critical point occurs at the ambient temperature below which a homeothermic animal must produce heat to maintain a stable body temperature. The upper critical temperature is ambiguous and has been defined in multiple ways (Mount, 1973; Silanikove, 2000). The initial defenses a ruminant employs against heat stress are sweating, vasodilation, and respiration (Silanikove, 2000). If homeothermy is maintained under these conditions, stress is minimal and production is generally not diminished. When ambient temperature and humidity increases such that initial cooling mechanisms fail to maintain body temperatures, the animal has one last line of defense before body temperatures rise: reduce DMI and thereby lower the rate of metabolism. This is the point where heat stress has a direct effect on animal productivity. If temperatures continue to rise past the animal's capacity to reduce internal heat load through reduced metabolism or if the temperature increase was too sudden for the animal to adapt by reducing DMI, the body temperature of the animal increases. Thus the core body temperature of an animal is a useful method for determining the level of severe heat stress, although it is important to understand that negative effects on productivity can occur prior to a noticeable change in body temperature.

Removing thermal radiation load on animals to lower their body temperature is more difficult than just providing shade, as only about 30% of the total radiation on a sunny day comes directly from the sky (Kelly et al., 1950; Bond et al., 1967). Diffuse solar radiation and reflected radiation from the ground or other objects can contribute significantly to total thermal radiation and are not completely intercepted by overhead shade. The lower the shade is to the animal, the more diffuse and reflected radiation will be intercepted. Livestock rely heavily on evaporative cooling to reduce heat loads and thus air flow can be beneficial in reducing cattle heat loads (Ittner et al., 1955). Also with regard to evaporative cooling potential, while trees can increase humidity levels, they also allow for improved air circulation and can cool surrounding air through evaporation of moisture from leaves, or transpiration (Shashua-bar et al., 2009). With the variable impacts of these different factors, it is not clear what effect tree shade will have on livestock body temperatures.

The objective of this study was to determine the effect of two tree species in silvopastures on the vaginal temperatures of lambs. It was hypothesized that the lambs in the silvopastures would be cooler throughout much of the day and experience less fluctuation in day to night temperature change.

Materials and Methods

All procedures were approved by the Virginia Tech Institutional Animal Care and Use Committee under protocol number 14-075. Forage and livestock management practices were reported in Chapter II.

Weather

Weather data were collected from a weather station located on Kentland Farm, about 500 m from the study site. Variables included air temperature (°C), relative humidity (%), gross radiation (kw · m^{-2}), and precipitation (0.01-in.). THI was calculated according to Mader et al. (2006)

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

where AT is air temperature (°C) and RH is relative humidity (%) measured by the Kentland Farm weather station. Historical weather data (1981-2010) was collected from http://www.weather.gov/rnk/MonthlyClimateNormals under Blacksburg, including average minimum and maximum temperatures and total precipitation by month.

Lamb vaginal temperatures

Blank controlled internal drug release (CIDR) devices for sheep were provided by Zoetis Animal Health (Parsippany, NJ). A roughly 2-cm segment was removed from the device and replaced with a Star Oddi Data Storage Tag (DST) micro-T temperature logger (Star Oddi, Iceland). The logger was preprogrammed through a communication box and Mercury software (Star Oddi, Iceland) to record temperature every ten minutes. The whole device was sealed with Super 33+ vinyl electrical tape (3M Company, Maplewood, MN). High-visibility orange flagging tape was tied to the end of the CIDR device in case of inadvertent elimination from the ewes during deployment. Devices were inserted into the vagina of the ewes to be tested with an

EAZI-Breed CIDR sheep applicator (Zoetis Animal Health, Parsippany, NJ) after being lubricated with a non-spermicidal all-purpose lubrication jelly.

At the start of each measurement period, three sheep in each experimental unit of block one (*n* = 9) were equipped with the vaginal temperature loggers for three days. Loggers were transferred to test sheep in the consecutive blocks the following two weeks. Devices were sterilized with 80% ethanol solution in between measurement periods. In 2014, after sheep temperatures had been collected in all experimental units (three weeks), the measurement rotation was restarted in the fourth week. During this year, the same loggers were redeployed in the same ewes each rotation. In 2015 and 2016, each three week measurement period was followed by a week of no measurements and data collection was restarted in the fifth week. During these years, the loggers were randomly assigned to ewes each measurement period. Data collection was concluded after three rotations through each experimental unit. In the case of inadvertent elimination of sensors from the ewes, the devices were reinserted in some cases, while they were not reinserted if the remaining measurement period was deemed to be too insufficient in length to gain meaningful data.

Data were downloaded to a desktop computer using a communications box and Mercury software (Star Oddi, Iceland). Data were exported to Microsoft Excel v. 2013 (Microsoft Corporation, Redmond, WA) and labeled with designated treatment, block, DST micro-T device, sheep, month, day, year, hour and minutes. Data points collected from loggers when not in ewes during the measurement period were deleted from the dataset. All data points three standard deviations from the mean were deleted from the dataset.

A calibration of the sensors was completed in the second year prior to study initiation and in the third year following study conclusion. For this calibration, a beaker was filled with distilled water and all temperature sensors, which were set to log temperature every minute, were placed in the water bath. A Comark PDT300 waterproof digital thermometer (Comark Instruments, Norwich, Norfolk, UK) was also placed in the water bath. The beaker was placed on a hot plate and the water was heated until it reached about 43 °C and then removed from the hot plate. At one-minute intervals, temperature readings of the waterproof thermometer were recorded six times and later compared to the corresponding measurements of the sensors. The measures collected by the standard were regressed against the measures collected by each sensor and the equation of the line and R^2 were calculated for each sensor in Microsoft Excel v. 2013 (Microsoft Corporation, Redmond, WA). These equations were used to correct all data measurements taken during each study period with the sensors.

Statistical analysis

Using a linear mixed-effects model in R statistical software (R Package, http://www.R-project.org/), data for each treatment were fitted to a cubic mixed model of the equation:

$$y = \beta_0 + \beta_1(m) + \beta_2(t) + \beta_3(t)^2 + \beta_4(t)^3 + \varepsilon_S + \varepsilon_E$$

where *y* is the adjusted vaginal temperature, *m* is the month, *t* is the time in minutes from the start of the day over total minutes within the day, ε_S is the random effect associated with each sheep, and ε_E is the experimental random error. The sheep random effects (ε_S) follow a normal distribution with a mean of zero and a covariance matrix which has a general positive-definite structure and is estimated with Log-Cholesky parameterization. The model diagnostics for this mixed effects model were conducted before statistical inference. The mean and variance of each coefficient (β_i) was calculated by treatment. The test statistic was computed along with P values to detect any differences in equation coefficients for each treatment using the T-test. The model was used to compare each treatment by hour for any differences. Differences were considered significant when $P \leq 0.05$ and trends when $P \leq 0.10$.

The relationship between the air temperature or the THI and vaginal temperatures of the lambs was also determined using a linear mixed-effects model in R statistical software (R Package, http://www.R-project.org/). Data for each treatment were fitted to a quadratic mixed model of the equation

$$y= \beta_0+ \beta_1(T)+\beta_2(T)^2+\varepsilon_S+\varepsilon_E$$

where y is the adjusted vaginal temperature, T is the air temperature measured at the same hour that the vaginal temperatures were measured, ε_S is the random effect associated with each sheep, and ε_E is the experimental random error. For the analysis of the relationship between the THI and the vaginal temperatures of the lambs, THI, in place of ambient temperature, was included in the model. The sheep random effects (ε_S) follow a normal distribution with a mean of zero and a covariance matrix which has a general positive-definite structure and is estimated with Log-Cholesky parameterization. The model diagnostics for this mixed effects model were conducted before statistical inference. The mean and variance of each coefficient (β_i) was calculated by treatment. The test statistic was computed along with P values to detect any differences in equation coefficients for each treatment using the T-test. The model was used to compare each treatment by hour for any differences. Differences were considered significant when $P \leq 0.05$ and trends when $P \leq 0.10$.

Results

Weather

Temperatures during the summer of 2014 were similar to or cooler than the historical average. Summers of 2015 and 2016 had hotter average minimum and maximum temperatures than the historical average (Table 4.1). 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. 4.1). Although conditions were within uncomfortable (70.0-74.9) and stressful (75.0-79.9) bounds throughout most of each summer, 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 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. In 2014, the maximum THI was 79.7, 80.1, 79.0, and 79.4 for June, July, August, and September, respectively. In 2015, the maximum THI was 75.4, 80.6, 80.4, and 79.1 for May, June, July, and August, respectively. In 2016, the maximum THI was 76.7, 79.9, 83.3, and 81.0 for May, June, July, and August, respectively.

In terms of solar radiation, on average, 2015 had sunnier days than the other two years (Fig. 4.2). Solar radiation was similar in 2014 and 2016.

As mentioned previously, spring was dry for all three years compared to the historical averages, and this was particularly the case in 2014 (Fig. 4.3). Precipitation in August of 2014lowered the THI in that month (Fig. 4.1). Despite a dry May in 2015 and 2016, conditions were generally stable for the latter three months of the study in those years.

Lamb vaginal temperatures

The adjustments provided by the equations for each Star Oddi sensor were minimal (Table 4.2).

Lambs in the silvopastures experienced fluctuations in vaginal temperatures of smaller amplitude than lambs in the open pastures (Table 4.3). This is evident by the larger coefficients for time (β_2, β_3, and β_4) in the cubic fitted line for the vaginal temperatures of the lambs in the open pastures. These coefficients were significantly larger in the open pasture system (Table 4.4).

Lambs in the black walnut silvopastures had lower vaginal temperatures than lambs in the open pastures from 1300 to 1700 h (Table 4.5; Fig. 4.4) and tended to have lower vaginal temperatures at 1800 h. Lambs in the black walnut silvopastures also tended to have cooler vaginal temperatures than lambs in the honeylocust silvopastures from 1400 to 1600 h and again at 1800 to 2000 h. Lambs in the honeylocust silvopastures tended to have hotter vaginal temperatures than lambs in the open pastures during 700 and 800 h.

Fewer data points were collected in May, resulting in more fluctuations in body temperature measures (Fig. 4.5). Nevertheless, lambs in the open pastures had hotter peak temperatures than lambs in the silvopastures. In June, lambs in the honeylocust silvopastures had lower vaginal temperatures than lambs in the other systems throughout most of the day (Fig. 4.6). Lambs in the black walnut silvopastures experienced less variation in day-to-night temperature changes than lambs in the other systems. In July, vaginal temperatures of lambs in the honeylocust silvopasture and lambs in the open pastures were similar, although the lambs in the honeylocust silvopastures were warmer during the early morning hours (Fig. 4.7). Lambs in the black walnut silvopasture remained cooler and had more stable vaginal temperatures over time. In August, peak temperatures for lambs in the honeylocust silvopasture rose above the peak temperatures for lambs in the open pastures (Fig. 4.8).

Lambs in the honeylocust silvopastures had increasingly hotter peak body temperatures from June through August (Fig. 4.5-4.8). In contrast, lambs in the black walnut silvopastures had lower peak body temperatures as the months increased, while lambs in the open pastures experienced little change in peak body temperatures with month. This phenomenon is also evident in the coefficient for month (β_1) in the cubic fitted equations, where a negative value was computed for the black walnut silvopasture equation, and a greater value was computed for the honeylocust silvopasture equation than for the open pasture equation (Table 4.3).

The relationship between air temperature and lamb vaginal temperature was greater than the relationship between THI and lamb vaginal temperature for the lambs in the black walnut silvopastures and the open pastures, but not the honeylocust silvopastures (Table 4.6). The relationships for both ambient conditions and lamb vaginal temperature was greater for the lambs in the open pastures, followed by the relationships for the lambs in the honeylocust silvopastures, and finally the lambs in the black walnut silvopastures. The relationship between air temperature and lamb vaginal temperature had a significantly steeper slope for the lambs in the open pastures than the lambs in the silvopastures (Table 4.7, 4.8). The relationship between THI and lamb vaginal temperature had a significantly steeper slope for the lambs in the open pasture than the lambs in the silvopastures (Table 4.9, 4.10).

Discussion

Lamb vaginal temperatures

The body temperatures collected in this study were not different from other measures of core body temperatures in lambs. Sheep in the TNZ typically have rectal temperatures between 38.3 and 39.9 °C, and temperatures at or above 42.0 °C indicate that a sheep is experiencing severe heat stress that could lead to significant damage (Marai et al., 2007). Only sheep in the black walnut silvopastures consistently had body temperatures below the upper limit of 39.9 °C for all months except June, in which the body temperatures of the lambs in these systems approached 40.1 °C. In addition, during the hours of 1300 to 1700 h, the lambs in the black walnut silvopastures were significantly cooler than lambs in the open pastures.

The capacity for measuring rectal temperatures – the traditional measure of core body temperatures – in free-range livestock is limited to equipment that can automatically log and transmit or store the data. The effectiveness of fixed rectal thermometers is also limited by the restriction of fecal matter flow. On the other hand, vaginal temperature sensors have been designed to be left in free-ranging cows for extended periods of time with little interference on the animal (Burdick et al., 2012). Vaginal temperature – although limited in use to cows, ewes, or does – was well correlated with rectal temperature and other measures of core body temperatures (Burdick et al., 2012). This was the first study known to the authors that used vaginal temperature loggers in modified CIDRs for grazing sheep. The method worked well, though occasionally the devices would fall out or be pulled out by an inquisitive lamb in the same experimental unit. It is recommended that future researchers provide for this possibility and affix a high-visibility ribbon to the end of each device for ease of recapture in the field.

Other studies have shown similar reductions in body temperature for livestock provided with shade. Within a New Zealand pasture, dairy cows grazing during the summer months had lower mean vaginal temperatures during the day when provided with shade (38.6 °C versus 38.7 °C) despite relatively mild weather during the study (Kendall et al., 2006). The greatest differences occurred, as expected, during the hottest part of the day. Similar results were reported in another temperate environment study on dairy cows (Fisher et al., 2008). Body temperature benefits from shade were even more dramatic in subtropical Florida, where dairy cows provided with shade had body temperatures of 38.9 °C compared to 39.4 °C for dairy cows without shade (Roman-Ponce et al., 1977).

However, dairy cows, with higher metabolic rates and lower surface to volume ratios, might be expected to be more susceptible to heat stress than sheep. Johnson (1991) collected body temperatures and respiratory rates of free-ranging Merino sheep in and out of shade during the summer months and yet they found no difference in body temperature for sheep that used shade and sheep that did not use shade as heavily. Certainly the lack of clearly-imposed treatments could have led to these inconsistent results.

It is not immediately clear why there was no overall difference in vaginal temperatures of lambs in the honeylocust silvopastures and lambs in the open pastures. Attempts to measure ambient temperatures within the three treatments were unsuccessful because thermometers were attached to fixed points (fence posts) within the systems, resulting in discontinuous measures of tree shade effects (data not published). Unlike fence posts, lambs were observed to move throughout the day, and spend the majority of their time in the shade.

Differences in body temperatures likely were a function of tree morphology. The leaf structure and canopy architecture of honeylocust trees leads to a lighter shade than the deeper shade of the black walnut trees (Brown and Gillespie, 1990; Buergler et al., 2006). In addition, the canopies of the black walnut trees were wider, deeper, and lower than the canopies of the honeylocust trees (Buergler, 2004). Brown & Gillespie (1990) used a micrometeorological computer model to estimate the radiation load on a person standing underneath different species of trees in the winter, spring, and summer. Under black walnut trees, it was calculated that a person would receive 380 $W \cdot m^{-2}$ compared to 422 $W \cdot m^{-2}$ under a honeylocust tree in the summer months. On a three-part comfort class scale (comfortable, desire to be cooler, desire to be much cooler), the two species of trees differed by a single class in the model. The body temperatures of the lambs in the honeylocust silvopastures increased slightly each month, which might correspond with increasing leaf drop by the honeylocust trees into the late summer months (Smitley and Peterson, 1996; Buergler et al., 2006). Future studies should investigate the radiation intercepted over time by these trees. Nevertheless, the animals in the honeylocust silvopastures heavily utilized the shade from these trees throughout all months (Chapter III), and it is thus surprising that the body temperatures of lambs in the honeylocust silvopastures did not differ from body temperatures of lambs on control pastures.

Another possible hypothesis for similar body temperatures for lambs in honeylocust silvopastures and the open pastures could be that the lambs in the honeylocust silvopastures were less heat stressed and thus had greater DMI. Greater metabolic rates accompany greater DMI, which can lead to a rise in body temperature (Blackshaw and Blackshaw, 1994). Lambs spent similar amounts of time grazing in the honeylocust silvopastures (Chapter III), but evidence from pre- and post-graze herbage mass estimates suggests the lambs in the honeylocust silvopastures tended ($P = 0.1244$; Chapter II) to have greater levels of intake than lambs in the open pastures. It should be noted that on this basis, lambs in the black walnut silvopastures also had greater levels of intake than lambs in the open pastures ($P = 0.0269$). In addition to difference in intake, the forages in the honeylocust silvopastures were found to be more nutritious than forages in the open pastures in terms of greater protein content ($P < 0.0001$) and lower neutral detergent fiber concentrations ($P = 0.0052$). High roughage diets produce greater levels of heat during fermentation than less fibrous diets (Lu, 1989; Blackshaw and Blackshaw, 1994). Under conditions of heat stress, sheep fed less fibrous feeds do not reduce feed intake to the degree that occurs with sheep fed high fiber feeds (Bhattacharya and Hussain, 1974). Thus, while higher nutrition forages themselves may have a lower heat of fermentation per dry weight of forage, the increased intake by animals fed these forages may actually lead to an increase in total metabolic heat produced.

The case for nutrition-driven elevation in peak body temperatures in honeylocust silvopastures is supported by the fact that peak body temperatures of lambs in these systems did not occur during the hottest time of the day – as was the case for lambs in open pastures – but at 1900 h. The time lag observed for cattle heart rates to increase after feed consumption is about 30 to 60 minutes and this increase can continue for several hours (Brosh et al., 1998) and this pattern would likely be a reasonable model for responses in sheep. The evening grazing bout for lambs in these systems began roughly around 1600 to 1800 h and continued until about sunset, or about 2200 h (Chapter III). A similar rise in vaginal temperatures occurred for lambs in all treatments from 500 to 700 h, which coincided with the morning grazing bout. These observations support the hypothesis that greater levels of intake and activity of lambs grazing in the honeylocust silvopastures in the late afternoon masked the cooling effect of the honeylocust trees during those early evening hours.

Sheep in the silvopastures also experienced less day to night temperature fluctuations, although it is unclear whether this is a benefit or not. A decline in body temperatures at night, during what has been termed “nighttime recovery” (i.e., conditions where the THI is less than 72 for 5 to 10 h), has been considered essential for feedlot cattle to cope with daytime heat stress (Hahn and Mader, 1997; Hahn, 1999; Nienabar and Hahn, 2007). In Arizona, the upper critical THI for dairy cows was a minimum of 64 and a maximum of 76; the cows needed a nighttime drop in temperature to a THI of 64 to adequately cool off from the heat of the day (Igono et al., 1992).

Dairy cows provided with lengthened night cooling conditions or lowered nighttime temperatures had average rectal temperatures that approached the rectal temperatures of cows in a thermoneutral environment more so than the rectal temperatures of cows with lower peak afternoon temperatures (Scott et al., 1983). This was interpreted as indicating that the nighttime dissipation of stored body heat is more important for maintaining body temperatures than reduced daytime temperatures. The researchers posited that livestock require diurnal variation in body temperatures, and daytime cooling strategies are not sufficient to keep livestock cool. In some cases, these strategies might actually have a deleterious effect on livestock body temperatures. The advantage of cooling directly to an open nighttime sky in the open pasture could have also been a reason for the similar afternoon body temperatures for lambs in the open pastures and the honeylocust silvopastures.

The trees in the silvopastures modulated the effect of ambient conditions on the body temperatures of the lambs. Ambient conditions – both air temperature and THI – had less of an influence on lamb vaginal temperatures for the lambs in the silvopastures than lambs in the open pastures. Lambs in the black walnut silvopastures demonstrated the poorest relationship between ambient conditions and lamb vaginal temperatures. The fitted lines for the relationship between ambient conditions and lamb vaginal temperatures for the lambs in the open pastures also had steeper slopes and lower intercepts than the fitted lines for the lambs in the silvopastures. This indicates that the body temperatures of the lambs in the open pastures more closely followed changing ambient conditions. In a study of dairy cattle provided with two different amounts of shade, the body temperatures of all the cows in the study increased with increases in ambient temperatures, but the slope of increase for cows in the heaviest shade treatment (9.6 m^2 shade ·

cow^{-1}) was lower than the slope of increase for cows in the moderate (2.4 m^2 shade · cow^{-1}) and no shade treatments (Schütz et al., 2010).

Conclusion

While the deeper shade of black walnut trees kept lambs in these silvopastures 0.4 °C cooler during the hottest parts of the day (1300 to 1700 h), the lambs in the honeylocust silvopastures had similar vaginal temperatures, and in one month hotter peak temperatures (August), than lambs in the open pastures. The reason for this latter phenomenon is not clear, although it may be tied to declining shade cover provided by these trees over the growing season or to more nutritious forage consumption by the lambs in these systems. Lambs in the silvopastures experienced less amplitude in diurnal temperature variation due to the modulating effect that the shade from the trees had on lamb body temperatures in the silvopastures. The variable effect of tree species on animal physiology may be an important consideration for producers designing a silvopasture system.

Table 4.1. 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-year averages (1981-2010) at Kentland Farm, Blacksburg, VA.

	Year											
	2014			2015			2016			30-yr average		
Month	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	110.0
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

Table 4.2. Regression equations for calibration of Star Oddi sensors.

Star Oddi sensor	Regression equation	R^2
7241	y = 0.9151x + 2.8616	0.9661
7242	y = 0.9125x + 3.4229	0.9532
7247	y = 0.9693x + 1.0732	0.9991
7248	y = 1.0556x - 1.4119	0.9991
7254	y = 0.9253x + 2.6809	0.9986
7258	y = 0.9741x + 0.8518	0.9992
7259	y = 0.9294x + 2.8026	0.9913
7260	y = 0.9469x + 1.8444	0.9888
7261	y = 0.9277x + 3.0976	0.9600

Table 4.3. Estimate (Mean) and standard error (SE) for coefficients for the equations of the cubic fitted line for each treatment. β_0 is the intercept, β_1 is the coefficient for month, β_2 is the coefficient for time, β_3 is the coefficient for the quadratic time function, and β_4 is the coefficient for the cubic time function.

	β_0		β_1		β_2		β_3		β_4	
Treatment[1]	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
BW	40.3	0.12	-0.10	0.0042	-4.3	0.11	12.1	0.23	-8.0	0.16
HL	38.7	0.13	0.17	0.0045	-4.9	0.13	14.0	0.24	-9.4	0.16
OP	39.2	0.08	0.08	0.0045	-6.4	0.12	19.6	0.24	-13.7	0.16

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

Table 4.4. Test statistic comparisons of equations of cubic fitted line for each treatment. β_0 is the intercept, β_1 is the coefficient for month, β_2 is the coefficient for time, β_3 is the coefficient for the quadratic time function, and β_4 is the coefficient for the cubic time function

	B_0	**B_1**	**B_2**	**B_3**	**B_4**
Treatment[1]	T stat[2]	T stat[2]	T stat[2]	T stat[2]	T stat[2]
BW vs. HL	1554.21	-7191.57	595.39	-909.90	980.24
BW vs. OP	1381.91	-4812.13	2131.01	-3689.38	4228.64
HL vs. OP	-499.16	2308.49	1372.10	-2652.10	3101.59

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

[2] $P \leq 0.0001$ for all comparisons of coefficients

Table 4.5. Comparison of mean lamb vaginal temperatures by hour. Standard error was 0.1 for all measures.

	Treatment[1]			Tukey's adjusted P-values[1]		
Hour	BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
	----- Temperature -----					
0000	39.5	39.7	39.4	0.4270	0.9570	0.2690
0100	39.4	39.6	39.4	0.4310	0.9760	0.3060
0200	39.3	39.5	39.3	0.3900	1.0000	0.3700
0300	39.3	39.5	39.3	0.5080	0.9920	0.4220
0400	39.2	39.4	39.2	0.4310	0.9860	0.3310
0500	39.2	39.4	39.2	0.4650	0.9850	0.3600
0600	39.3	39.4	39.1	0.5970	0.7130	0.1830
0700	39.1	39.3	39.0	0.4237	0.6618	0.0843
0800	39.2	39.3	39.1	0.3418	0.7865	0.0952
0900	39.3	39.5	39.3	0.2540	0.9680	0.1550
1000	39.4	39.6	39.5	0.2510	0.7040	0.6920
1100	39.4	39.6	39.6	0.2380	0.2560	0.9970
1200	39.5	39.7	39.7	0.2600	0.1020	0.8960
1300	39.5	39.8	39.9	0.1931	0.0202	0.6317
1400	39.6	39.9	40.0	0.0857	0.0050	0.5952
1500	39.7	40.0	40.1	0.0784	0.0018	0.4371
1600	39.8	40.1	40.2	0.0856	0.0041	0.5507
1700	39.8	40.1	40.2	0.1518	0.0176	0.6770
1800	39.9	40.1	40.2	0.0877	0.0597	0.9913
1900	39.9	40.1	40.1	0.0802	0.2168	0.8640
2000	39.8	40.0	39.9	0.0989	0.5816	0.5149
2100	39.6	39.8	39.7	0.3260	0.9670	0.4510
2200	39.5	39.7	39.5	0.4270	1.0000	0.4150
2300	39.5	39.7	39.5	0.3490	1.0000	0.3360

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

Table 4.6. Indicators of fit for the relationships of ambient conditions to lamb vaginal temperatures by treatment.

	Air temperature to vaginal temperatures			THI to vaginal temperatures		
Treatment[1]	AIC[2]	BIC[3]	logLik[4]	AIC[2]	BIC[3]	logLik[4]
BW	7237.81	7282.96	-3611.90	7271.63	7316.79	-3628.82
HL	6840.79	6885.44	-3413.39	6801.24	6845.90	-3393.62
OP	6046.16	6091.01	-3016.08	6157.86	6202.70	-3071.92

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

[2] Akaike information criterion: lower is better

[3] Bayesian information criterion: lower is better

[4] Log-likelihood: higher is better

Table 4.7. Estimate (Mean) and standard error (SE) for coefficients for the equations of the quadratic relationship between air temperature and vaginal temperatures for all treatments. β_0 is the intercept, β_1 is the coefficient for air temperature, and β_2 is the coefficient for the quadratic air temperature function.

	B_0		**B_1**		**B_2**	
Treatment[1]	Mean	SE	Mean	SE	Mean	SE
BW	38.6	0.10	0.040	0.0016	-4.0e-8	2.4e-11
HL	38.5	0.11	0.055	0.0017	-5.5e-8	2.6e-11
OP	37.7	0.07	0.086	0.0015	-8.6e-8	2.2e-11

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

Table 4.8. Test statistic comparisons of equations of the quadratic relationship between air temperature and vaginal temperatures for all treatments.

	$\mathbf{B_0}$	$\mathbf{B_1}$	$\mathbf{B_2}$
Treatment[1]	T stat[2]	T stat[2]	T stat[2]
BW vs. HL	60.41	-437.59	437.58
BW vs. OP	521.80	-1424.96	1424.97
HL vs. OP	-399.43	907.43	-907.44

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

[2] $P \leq 0.0001$ for all comparisons of coefficients

Table 4.9. Estimate (Mean) and standard error (SE) for coefficients for the equations of the quadratic relationship between THI and vaginal temperatures for all treatments. β_0 is the intercept, β_1 is the coefficient for THI, and β_2 is the coefficient for the quadratic THI function.

	B_0		**B_1**		**B_2**	
Treatment[1]	Mean	SE	Mean	SE	Mean	SE
BW	38.7	0.10	0.031	0.0013	-3.1e-8	1.8e-11
HL	38.6	0.11	0.045	0.0013	-4.5e-8	2.0e-11
OP	37.9	0.07	0.067	0.0012	-6.7e-8	1.8e-11

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

Table 4.10. Test statistic comparisons of equations of the quadratic relationship between THI and vaginal temperatures for all treatments

	B_0	B_1	B_2
Treatment[1]	T stat[2]	T stat[2]	T stat[2]
BW vs. HL	63.65	-499.68	499.67
BW vs. OP	457.39	-1401.08	1401.09
HL vs. OP	-335.55	828.72	-828.74

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

[2] $P \leq 0.0001$ for all comparisons of coefficients

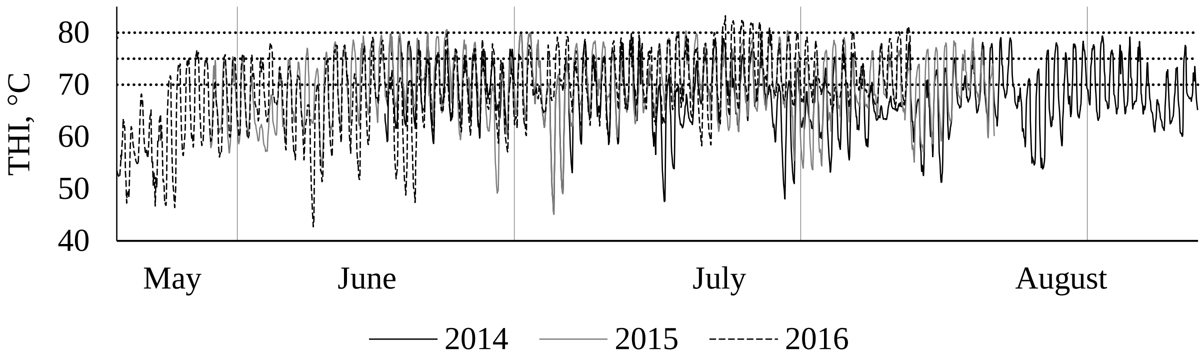


Figure 4.1. THI values as measured across the study period by year. Uncomfortable conditions = 70.0-74.9; stressful conditions = 75.0-79.9; severe heat stress > 80.0 (Silanikove, 2000).

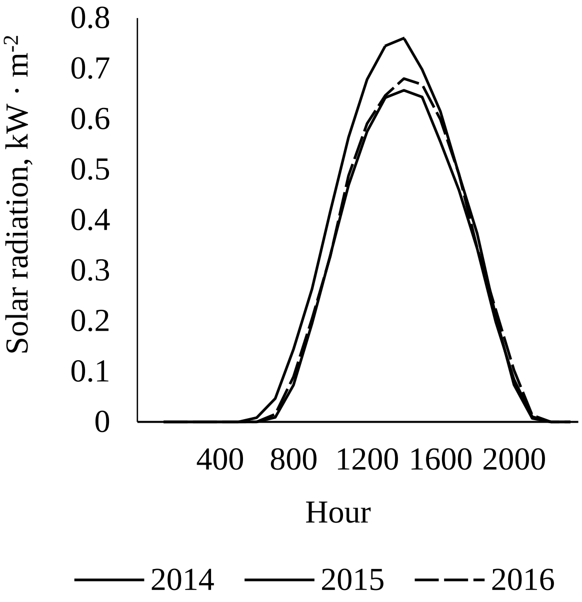


Figure 4.2. Mean solar radiation by year over a 24-hr period.

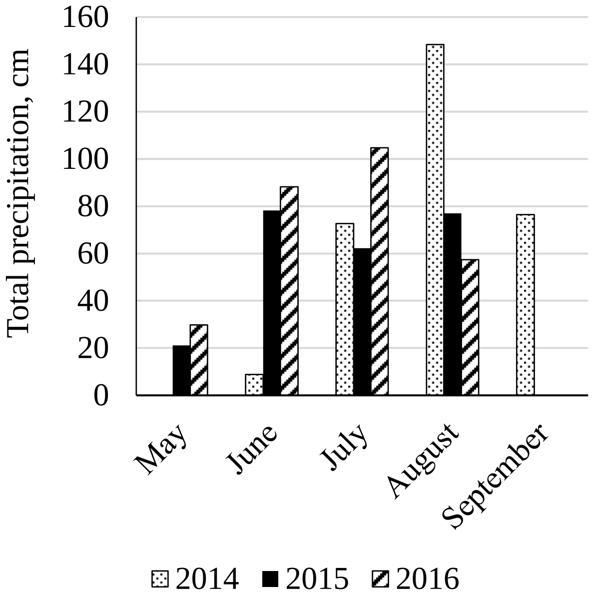


Figure 4.3. Monthly precipitation each year within the study period.

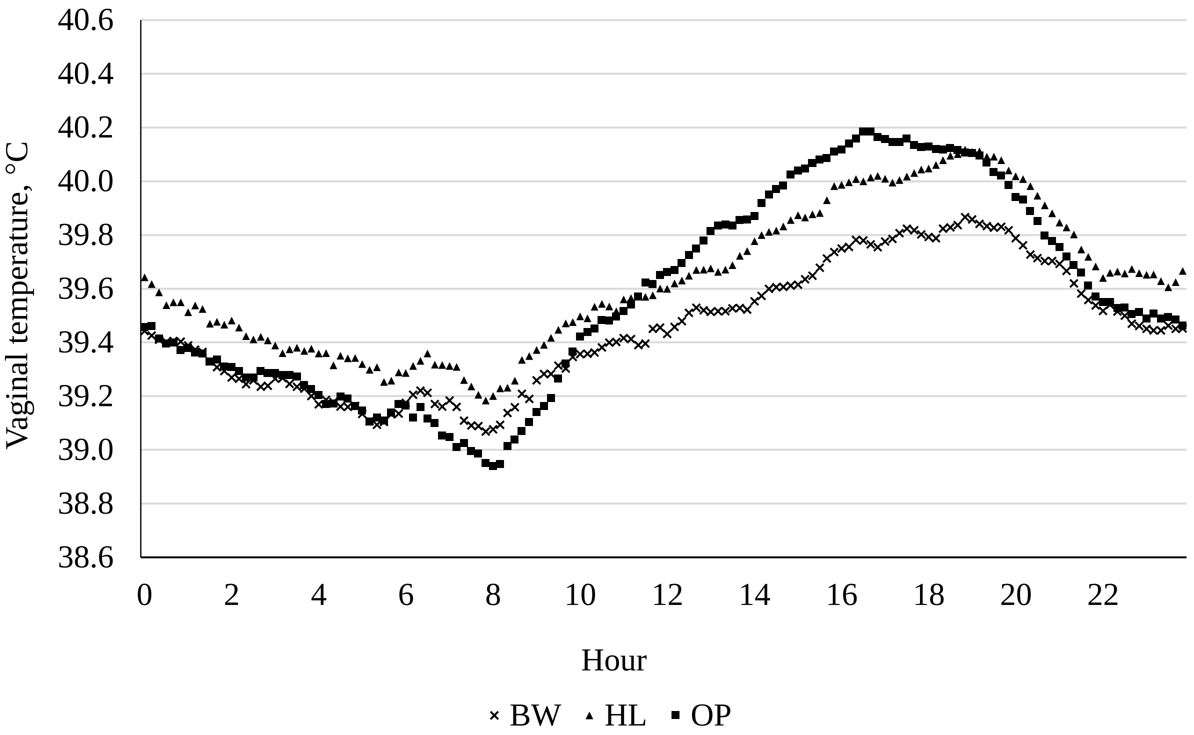


Figure 4.4. Mean vaginal temperatures of lambs by hour of day. Treatments: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture)

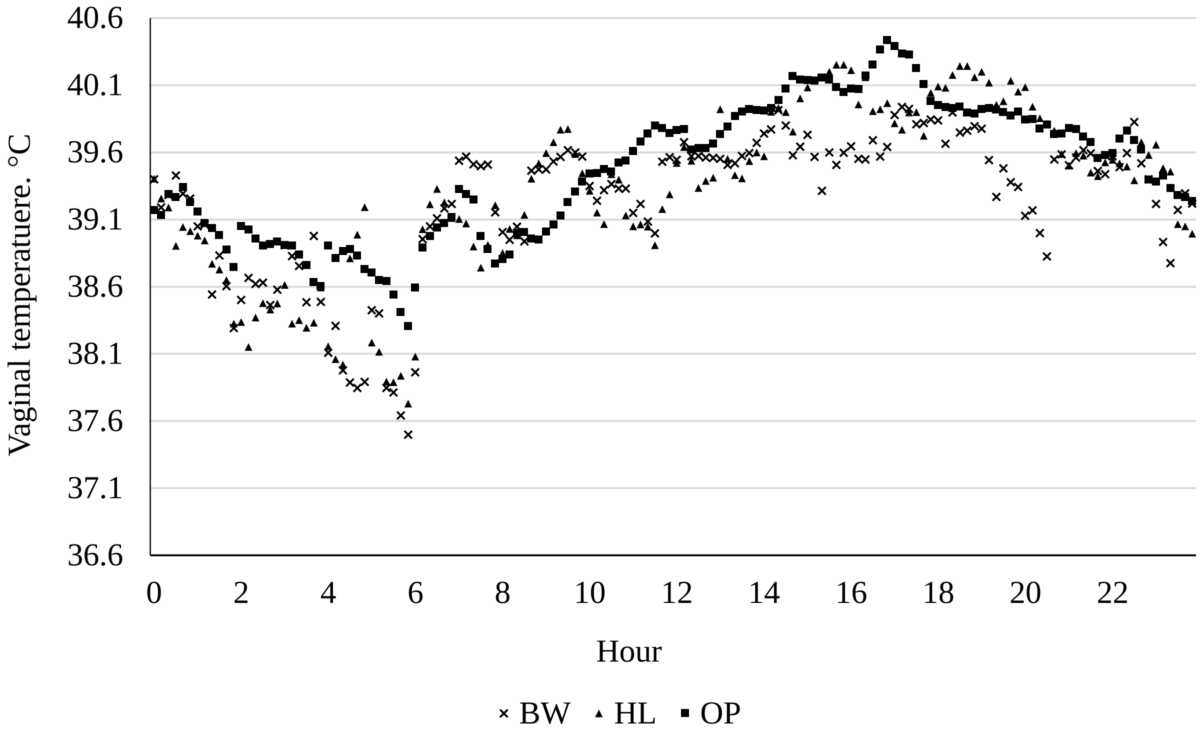


Figure 4.5. Mean vaginal temperatures of lambs by hour of day during May. Treatments: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

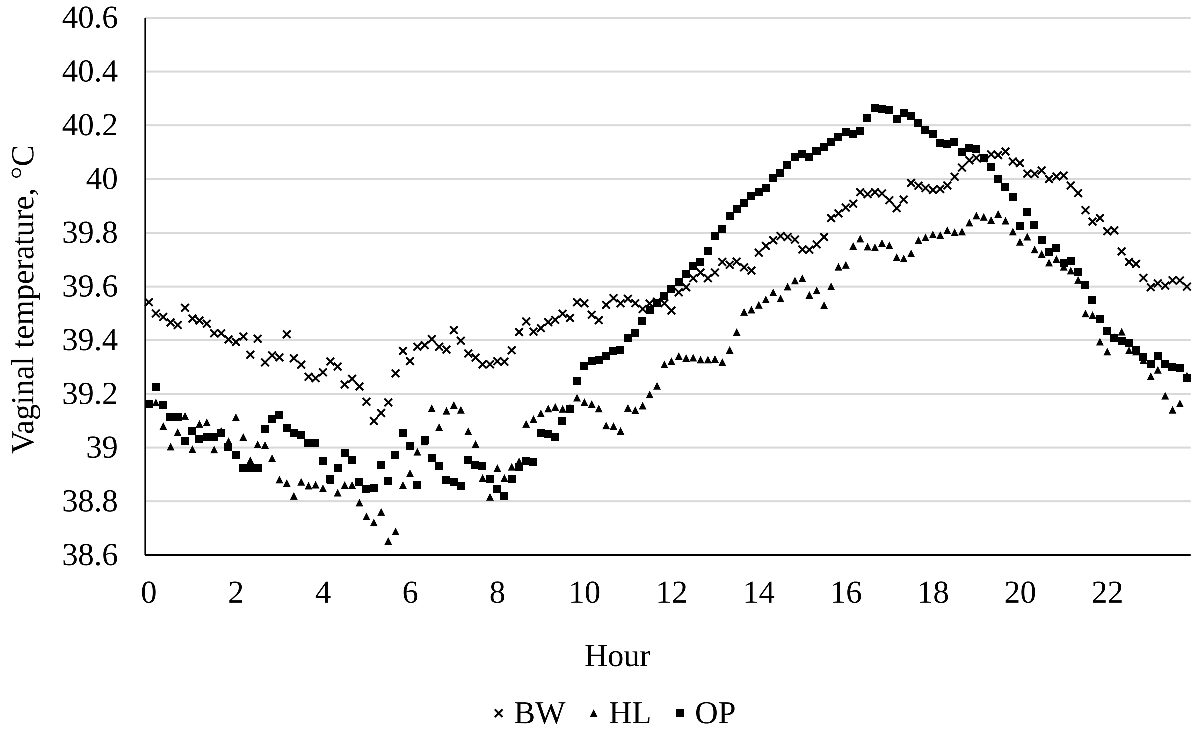


Figure 4.6. Mean vaginal temperatures of lambs by hour of day during June. Treatments: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

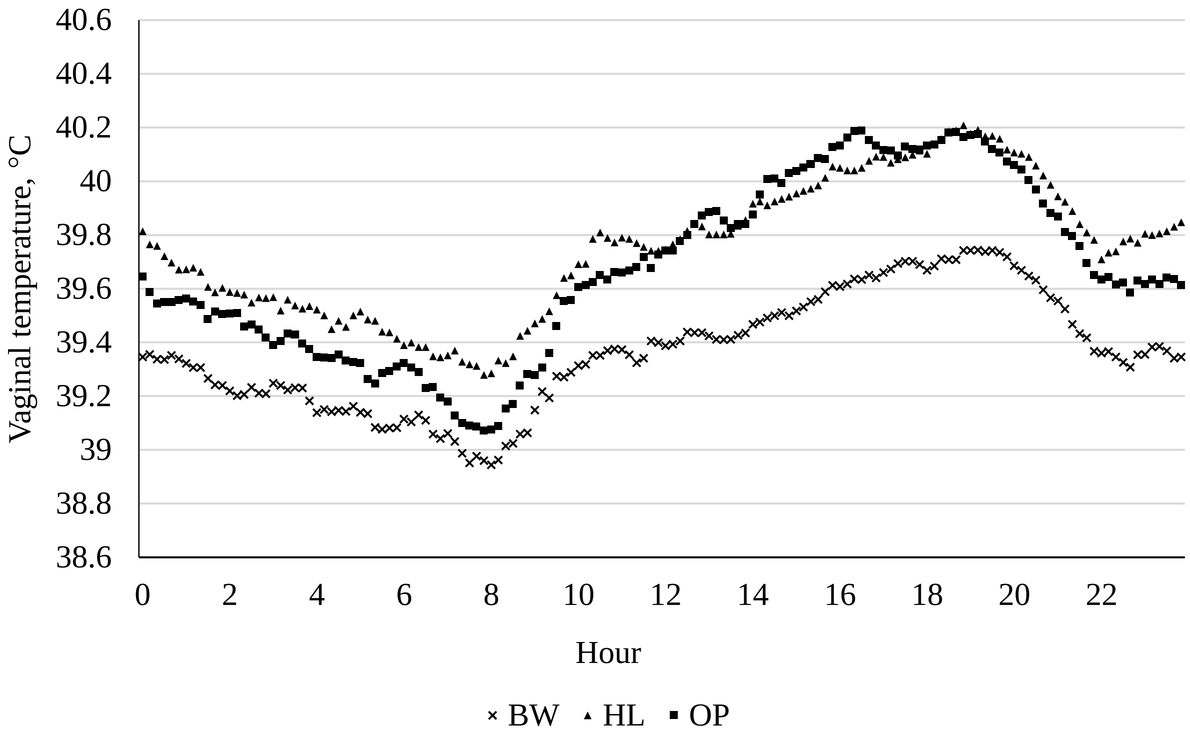


Figure 4.7. Mean vaginal temperatures of lambs by hour of day during July. Treatments: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

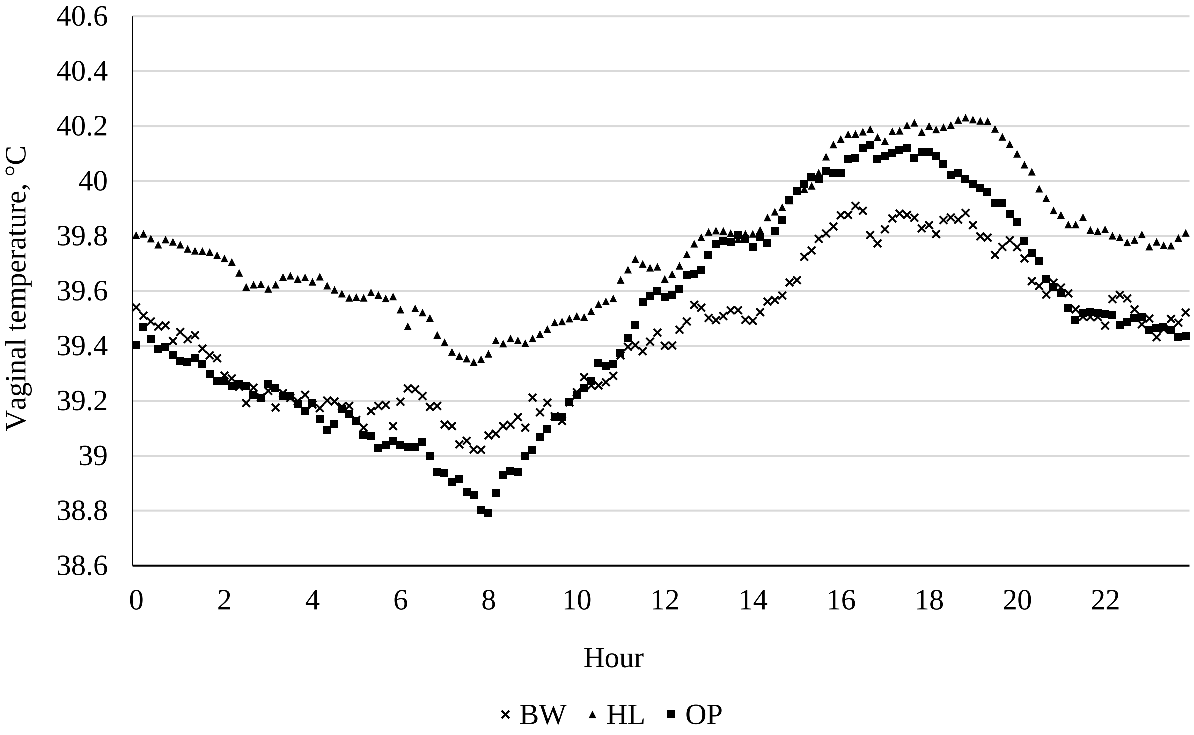


Figure 4.8. Mean vaginal temperatures of lambs during the entire study period by hour of day during August. Treatments: BW = black walnut silvopasture; HL = honeylocust silvopasture; OP = control (open pasture).

Chapter 5: Lamb productivity during the winter months in honeylocust and black walnut silvopastures

Abstract

Along with ecosystem provisioning, trees in silvopastures may provide forage-livestock systems with multiple goods and services, including shade, shelter, and browse. Little research has looked at the use of fodder trees in temperate silvopastures. Honeylocust (*Gleditsia triacanthos* cv. Millwood) trees were established in pastures to provide large, nutritious pods as supplemental fodder for livestock grazing the forage understory. The objective of this study was to determine the effect of these pods on lamb growth when animals grazed stockpiled tall fescue (*Schedonorus arundinaceus*). Animal performance in honeylocust silvopastures was compared with the productivity of lambs grazing open pastures and black walnut (*Juglans nigra*) silvopastures. The study was conducted as a randomized complete block design with three replications. Pre- and post-graze forage mass was estimated with a double sampling technique using a rising plate meter. Treatment pastures were rotationally stocked with three (walnut) or six lambs per experimental unit depending on forage availability. Fescue grab samples were collected every other rotation. Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and total digestible nutrients (TDN) were estimated with a robust equation using NIR spectroscopy. Pre- and post-graze pod mass per hectare was estimated using randomly placed quadrats. Lambs were naïve to pods and did not readily consume the fodder until four weeks into the trial, and the methods for estimating pod intake were not sufficient to detect pod differences in pre- and post-graze pod mass. Forage availability in the honeylocust silvopastures (5130 ± 90 kg $\cdot$ ha^{-1}) and open pastures (5050 ± 90 kg $\cdot$ ha^{-1}; $P=0.7580$) was greater ($P < 0.0001$) than forage availability in the black walnut silvopastures (3790 ± 90 kg $\cdot$ ha^{-1}). Treatment had no

effect (P = 0.3763) on average daily gains across the six weeks of the study. However, lambs within the honeylocust silvopastures had greater (P = 0.0251) average daily gains in the final period (0.12 ± 0.02 kg · day^{-1}) than lambs within the open pastures (0 ± 0.02 kg · day^{-1}), and lambs were observed consuming the pods. These data suggest that honeylocust pods may support greater gains of lambs, but that previous exposure and longer study periods in pasture settings may be necessary to see their nutritional benefit when grazing high quality forages.

Introduction

Along with ecosystem provisioning, trees in silvopastures may provide forage-livestock systems with multiple goods and services, including shade, shelter, and browse (Sharrow et al., 2009). Honeylocust (*Gleditsia triacanthos* L.) trees, which produce edible fodder and pods for grazing livestock, are particularly suitable for application in cool-season forage based pasture systems because of their leaf morphology and phenology. The double-compound leaf arrangement of honeylocust trees minimizes the obstruction of sunlight reaching the forage understory, while the distinct warm-season growth pattern of the tree complements the bimodal spring and fall growth pattern of cool-season forages (Scanlon, 1980; Sharrow et al., 2009). The pods produced by these trees also drop in early winter when forage production has otherwise ceased in temperate regions, providing livestock with a supplementary or alternative feed source on pasture (Scanlon, 1980; Wilson, 1991). Improved varieties of honeylocust trees (eg. ‘Millwood’) yield pods of greater size and with greater nonstructural carbohydrate content than those pods produced by unimproved honeylocust trees (Scanlon, 1980; Johnson et al., 2013).

The management goal for silvopasture systems is to intentionally enhance interactions between the numerous components such that increased or optimized services are provided by these systems. One such interaction might be that of combining an energy-rich feed, such as honeylocust pods, with a protein-rich feed, such as cool season forages, during the winter months for grazing livestock. The associative effect – when the effect of the combination is greater than the sum of the individual effects – of corn and cool season forages is well established (Dixon and Stockdale, 1999; Moore et al., 1999). Previous research has also demonstrated the nutritional similarity of Millwood honeylocust pods to whole ear corn (Wilson, 1991; Johnson et al., 2013). Early studies documented that honeylocust pods could replace oats in the rations (Atkins, 1942). Scanlon (1980) also reported that prior studies had documented that calves fed wildtype honeylocust pods had lower, but not significantly different, live weight gains as calves fed corn. It was hypothesized that providing honeylocust pods to sheep in combination with cool season forages would result in greater live weight gains and decreased forage consumption.

Materials and Methods

All procedures were approved by the Virginia Tech Institutional Animal Care and Use Committee under protocol number 15-182.

Research Site

This six-week winter grazing study took place at the Whitethorne Agroforestry Demonstration Center at Virginia Tech’s Kentland Farm in Blacksburg, Virginia (37.20 N 80.58 W). Soil series on the site include Berks-Lowell-Rayne complex, Unison and Braddock soils, and Weaver soils, arranged in order of decreasing slopes from 25-65%, 15-25%, and 0-5%, respectively.

Pasture Management

The silvopasture, including black walnut- (*Juglans nigra*) and honeylocust- (*Gleditsia triacanthos*) based silvopasturse, and open pasture treatments had been established in what was a uniform cool-season forage based pasture in 1995. The trees were thinned to a final density in

2012. After final thinning, trees were arranged in an approximate 12.2-m x 12.2-m configuration, with about 36 stems · ha^{-1}. Open and silvopasture treatments were replicated three times across the site in a randomized complete block design. The total area of each EU was 0.27 ha · EU^{-1}, and each EU was subdivided into four subpaddocks for rotational stocking.

Lambs grazed the pastures until the end of August of 2015. All pastures were then clipped to 13-cm and in early September, all black walnut silvopasture systems and the open system in block one were treated with 5 liter · ha^{-1} of Weedar 64 2,4-D amine broadleaf herbicide (Nufarm Ltd., Laverton, Australia) using a boom sprayer for stickweed (*Verbesina occidentalis*) control. Any large spots of stickweed throughout all other systems were also spot-sprayed with the same herbicide mixture using a backpack sprayer. Due to undesirable species and associated low productivity in the black walnut silvopastures, nitrogen was applied as urea at a rate of 67 kg · ha^{-1}. Afterwards, 1.3 kg of tall fescue (*Schedonorus arundinaceus* cv. Kentucky 31) and 0.3 kg of orchardgrass (cv. Benchmark+) were broadcast over each black walnut silvopasture EU, followed by two passes with a drag harrow.

Sheep and Stocking Management

Crossbred lambs (*n* = 50) were purchased from a Virginia producer with an average weight of 36-kg. Upon arrival to the research site, the lambs received a booster vaccination for *Clostridium perfringens* (November 12, 2015). They also received 8-cc of Cydectin Oral Sheep Drench (Boehringer Ingelheim, Vetmedica, INC., St. Joseph, MO) and 7-cc of Prohibit Levamisole Drench solution (AgriLabs, St. Joseph, MO). About two weeks later (December 8), the lambs' level of anemia was scored based on their lower eyelid according to the FAMACHA protocol as described by Kaplan et al. (2004). Any lamb with a score of 3 or greater received 7-cc of Prohibit Levamisole Drench solution (AgriLabs, St. Joseph, MO) and 10-cc of Panacur

Sheep Drench (Intervet Inc., Merck Animal Health, Madison, NJ). Prior to study initiation, the lambs were fed *ad libitum* hay as a single group on open (non-treatment) pastures adjacent to the research site until study initiation due to limited forage resources.

Lambs were stratified by sex and BW before being randomly assigned to each of the nine EUs. Because of lower forage availability, the black walnut silvopasture EUs received two ewes and one wether while the honeylocust and open pasture EUs received two ewes and four wethers.

The four subpaddocks in each EU were rotationally stocked with the assigned lambs on November 22. Sheep in all EUs were moved simultaneously to a fresh subpaddock once average residual forage heights reached about 7-cm.

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

Because lambs were native towards the honeylocust pods, several pods were cut into small pieces and mixed with roughly 0.5-kg of whole wheat grain. This mix was fed to each group of lambs within the honeylocust silvopastures. Lambs in the open pastures received 0.5-kg of whole wheat grain and the lambs in the black walnut silvopastures received 0.3-kg. Rations were refreshed when all the grain had been consumed by the sheep (November 23 and December 1, 5, and 9) and these feedings were concluded when the sheep in the honeylocust silvopasture EUs began to eat pods within the paddocks (roughly December 14). Due to evidence of coccidiosis within the lambs, lambs were provide with 0.18-kg · lamb^{-1} of 1.25% Corid pellets (Merial Inc., Duluth, GA) for five days (December 10-14).

BW, ADG, and System Gain

A livestock crate was used to confine lambs during weighing on Tru-Test load cells (Tru-Test, Ltd., Aukland, NZ). Average BW was calculated by averaging two un-shrunk BW measurements taken once per day for two consecutive days at days 0 (November 21) and 1, 14 and 15, 28 and 29, and 42 and 43. Each of these two week intervals was considered a single period.

ADG was calculated by dividing the average BW gain between periods by 14 days. 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.

Forage Mass

Forage availability and residual mass were estimated by taking 30 random measurements within each of the nine subpaddocks with a rising plate meter (Jenquip, Fielding, NZ) 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 the plate height, the area of the plate was marked with a round quadrat and the 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 four days, 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 forage availability on entry and residual on exit.

An estimate of individual intake was calculated as the difference between pre- and post-graze herbage mass divided by the total number of animals in the EU.

Forage Nutritive Value

At every other rotation, pure tall fescue (*Schedonorus arundinaceus*) samples were collected between 1200 and 1400 h from each subpaddock before entry by lambs. Samples were cut at a 5- to 8-cm residual height.

Samples were dried in a forced air oven at approximately 55 °C for at least four days. 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, Eden Prairie, MN) using ISIscan software (FOSS North America, Eden Prairie, MN). The Hay and Fresh Forage Master Equation from WinISI software (FOSS North America, Eden Prairie, MN) was used to calculate percent protein, NDF, and ADF. TDN was calculated by the equation

$$\mathrm{TDN} = 100.32 - 1.118 \times \mathrm{ADF}$$

Pod Productivity

Any stray or windblown honeylocust pods were removed from all non-honeylocust silvopasture subpaddocks prior to the study. At three random points within each EU prior to entry by the lambs, pods were collected from 1-m^2 quadrats and the fresh weight of the pods was weighed before being returned to the quadrats. Pod yield per hectare was calculated by multiplying the quadrat weights by 10,000. After the lambs had been moved from an EU, the same procedure was followed at the same points selected prior to lamb entry. Pod consumption was calculated by subtracting the post-graze measures from the pre-graze measures.

The fresh weight of 30 pods selected at random from each subpaddock was measured. Samples were dried in a forced air oven at approximately 55 °C for at least four days and then re-weighed. The moisture correction factor was calculated by dividing the dried weight by the fresh weight. However, the correction factor was not applied to any of the fresh weights as it never exceeded 1.008.

Statistical analysis

The rising plate meter regression was calculated using a linear function of sward height against forage mass of the double-samples with PROC REG in SAS Studio, v. 3.5 (SAS Inst., Cary, NC). All Cook's outliers calculated in the first iteration of the program were removed from the analysis. Pre- and post-graze herbage mass and intake estimates were calculated from the 30 random rising plate meter measurements using this equation.

A mixed ANOVA of ADG and system gain, pre- and post-graze forage herbage mass and intake estimates, and forage CP, NDF, ADF, and TDN content between treatments was calculated with PROC MIXED in SAS Studio, v. 3.5 (SAS Inst., Cary, NC). Experimental design was treated as a randomized complete block design with three replications. A repeated measures analysis by period was used with a compound symmetry covariance structure for the analysis of ADG. LS-means, standard error, and Tukey's adjusted differences of LS-means were calculated. Differences were considered significant when $P < 0.05$ and as trends when $P < 0.10$.

Results

ADG and system gain

The ADG of lambs in the honeylocust silvopasture was no different from the ADG of lambs in the black walnut silvopasture and open pasture ($P = 0.7699$; Table 5.1). The numerically greater ADG of lambs in the black walnut silvopastures offset the lower stocking rate of these systems and total system gain was no different between treatments ($P = 0.3763$).

However, there was a significant treatment by period interaction in the effect of treatment on ADG ($P = 0.0011$). Although there were no differences in ADG for lambs in all systems for the first two periods, lambs in the honeylocust silvopasture outperformed lambs in the open pastures during the third period (Table 5.2). During the third period, the ADG of lambs in the black walnut silvopastures was no different than the ADG of lambs in the other treatments.

Forage mass and intake

The R-squared value of the forage mass prediction model derived from the double samples was 0.6027 (Fig. 5.1).

Forage mass in the honeylocust silvopasture was no different from forage mass in the open pasture (Table 5.3). Both of these systems, however, produced more forage than the black walnut silvopasture system.

Although the goal was to keep post-graze herbage mass values constant across all treatments, they were only equal for the honeylocust silvopastures and open pastures (Table 5.3). Even with a lower stocking rate, the black walnut silvopastures had a lower post-graze herbage mass than the other systems.

No difference was estimated in individual forage intake (Table 5.3).

Nutritive value of tall fescue

All GH1 values for the prediction were no greater than 3.004 for all samples, while all NH1 values were no greater than 1.589 for all samples.

Tall fescue fescue CP content was greatest in the honeylocust silvopasture samples (Table 5.4). There was no effect of treatment on NDF (P = 0.2612), ADF (P = 0.1716), and TDN (P = 0.1727) in the tall fescue samples.

Pod productivity of the honeylocust trees

Mean honeylocust tree pod productivity in the silvopastures was high, but there was a wide range in values measured (Table 5.5). In some cases, post-graze pod measures were greater than pre-graze pod measures, and as a result, the corresponding disappearance numbers were negative. In some cases, pods that had fallen from the trees after the pre-graze pod measures may have contributed to the greater post-graze pod measures. There did not appear to be any correlation between the time when lambs were observed to begin consuming pods and consumption as estimated by these pod measurements. Nevertheless, lambs were observed to begin eating pods between the third and fourth weeks of the study (Fig. 5.2, 5.3).

Discussion

ADG and system gain

The live weight gains of the lambs decreased over the course of the study, likely a consequence of switching from feeding a low quality hay prior to the start of the study to providing a high quality forage at the initiation of the study. The lambs likely consumed high amounts of fresh forage during the first period, resulting in the highest ADG values, followed by compensatory gain and more moderate levels of intake in the second period. Gut fill and muscle development were likely lowest in the third period, which resulted in lower levels of gain for lambs in the black walnut silvopasture and open pasture systems. It could be that the consumption of honeylocust pods by the lambs in the honeylocust silvopastures masked this phenomenon, however.

Although there were no differences in ADG for lambs in all systems for the first two periods, lambs in the honeylocust silvopasture outperformed lambs in the open pastures during the third period. Coincidently, lambs were observed to begin eating pods between the third and fourth weeks of the study, or right before the conclusion of the second period. The significant increase in live weight gains for the lambs in the honeylocust silvopasture coincided with the point in time when the lambs finally began to consume the pods. Taken alone, this data seems to indicate that the consumption of pods by the lambs had a positive effect on their live weight gains. This effect, however, may be augmented by the sheltering effects of the trees, as demonstrated by the similar ADG of lambs in the black walnut silvopastures compared to the ADG of lambs in the honeylocust silvopastures during the third period. More work should be done to elucidate the benefits of animal comfort in the silvopastures during the early winter months compared to the benefits of pod intake alone.

Forage mass and intake

Similar work during the summer months in black walnut based silvopasture systems also has indicated depressed forage availability in these systems, while honeylocust trees appear to have little to no effect on forage productivity (Kallenbach et al., 2006; Fannon-Osborne, 2012). The results from this study also indicate that, in terms of plant biomass, anything produced by honeylocust trees (pods, leaf litter, timber, and belowground biomass) represents the net productivity of these systems over open pasture systems.

Although the goal was to keep post-graze herbage mass values constant across all treatments, they were lowest for the black walnut silvopastures. Due to the lower and less mature canopy of the forage sward in the black walnut silvopasture, the post-graze herbage mass values were likely underestimated in these systems by the overall forage mass regression equation.

It was hypothesized that pod consumption by the lambs would depress their forage intake. However, along with the delay in pod consumption, the methodology for forage measurement may have not been sensitive enough to pick up any differences in true individual animal intake. Future work should investigate the forage intake rates of sheep supplemented with honeylocust pods compared to sheep without any supplementation as they may be depressed (Loy et al., 2007) or unaffected (Brokaw et al., 2001).

Nutritive value of tall fescue

While previous reports have indicated that shade can lead to nitrate accumulation in forage (Stritzke et al., 1976; Lin et al., 2001), it is not clear why crude protein levels were higher in the honeylocust silvopastures at this time of the year when shade from the trees is minimal. Despite the evidence of greater crude protein in the tall fescue within the honeylocust silvopastures, it would not be expected to result in any difference in animal weight gains across these systems as crude protein within all tall fescue samples was adequate for growing lambs according to the Nutrient Requirements of Small Ruminants (National Research Council, 2007). The results from this study indicate that there is no effect of trees on the nutritional value of cool-season forages during the winter months.

Pod productivity of the honeylocust trees

The methods used to estimate pod consumption were not sensitive enough to detect pod intake by the lambs and did not account for windblown or stray pods, hence the occasional negative values of pod intake. Nevertheless, the pod productivity of these systems was significant. Because the forage productivity of the honeylocust silvopastures was equal to that of the treeless pastures, this significant pod productivity represented the harvestable net biomass productivity of these systems over conventional open pastures during the year of this study

(Sharrow et al., 2009). Unfortunately in this case, the realized value of this net primary productivity depended on the initially low voluntary intake of the pods by the lambs.

Eventually the lambs did begin to consume the honeylocust pods, demonstrating that naïve animals must acquire a taste for the pods before they will voluntarily consume them. As this study demonstrated, this could be facilitated by a training period wherein pods are fed in conjunction with a grain or other familiar and desirable feedstuffs. Other livestock, however, have been reported to consume the pods readily, including dairy cattle (Atkins, 1942), calves (Scanlon, 1980), and goats (personal observation).

Conclusion

The net biomass production of the honeylocust silvopastures, in terms of forage and pods, exceeded the biomass production of the open pastures during this study. Unfortunately the naïve lambs in this study were initially unfamiliar with pods. The improved weight gains that coincided with the witnessed initiation of pod consumption by the lambs indicate that there may be a benefit to live weight gains when honeylocust pods are consumed by lambs in a cool-season forage based system. Future studies should account for the training time necessary to introduce honeylocust pods as a fodder source to specific ruminant species. The potential for associative effects in these systems remains to be determined. Nevertheless, this study has documented the overyielding potential of honeylocust-based silvopastures towards net primary productivity, and these data suggest that live weight gains of sheep may be increased when honeylocust pods are consumed in combination with cool-season forages by growing lambs.

Table 5.1. Animal productivity in silvopastures and open pastures.

Treatment[1]			Tukey's adjusted P-values[1]		
BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
--------- ADC ± SE, kg · day^{-1} ---------					
0.17 ± 0.02	0.15 ± 0.01	0.15 ± 0.01	0.8071	0.7700	0.9964
------ System gain ± SE, kg · day^{-1} ------					
0.55 ± 0.22	0.89 ± 0.22	0.88 ± 0.22	0.4316	0.4562	0.9989

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

Table 5.2. Animal average daily gains in silvopastures and open pastures by period.

	Treatment[1]			Tukey's adjusted P-values[1]		
Period	BW	HL	OP	BW vs. HL	BW vs. OP	HL vs. OP
	------- kg · d^{-1} -------					
1	0.29	0.20	0.28	0.4572	1.000	0.2904
2	0.17	0.13	0.16	0.9732	1.000	0.9960
3	0.04	0.12	0	0.6308	0.9924	0.0251
SE	0.03	0.02	0.02			

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

Table 5.3. Forage productivity, residual forage, and calculated forage intake per lamb in silvopastures and open pastures.

Treatment[1]				Tukey's adjusted P-values[1]		
BW	HL	OP	SE	BW vs. HL	BW vs. OP	HL vs. OP
--- Pre-graze, kg · ha^{-1} ---						
3790	5140	5050	80	<0.0001	<0.0001	0.7580
--- Post-graze, kg · ha^{-1} --						
2880	3500	3340	90	0.0002	0.0041	0.3793
--- Intake, kg · day^{-1} ---						
1.52	1.57	1.66	0.08	0.8827	0.4407	0.7245

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

Table 5.4. Nutritive value of S. arundinaceus in silvopastures and open pastures.

Treatment[1]				Tukey's adjusted P-values[1]		
BW	HL	OP	SE	BW vs. HL	BW vs. OP	HL vs. OP
---- CP, % ----						
17.1	18.5	16.8	0.4	0.0321	0.8789	0.0116
---- NDF, % ----						
43.7	43.8	43.3	0.9	0.2611	0.9257	0.4404
---- ADF, % ----						
22.5	21.1	22.2	0.6	0.1798	0.9341	0.3119
---- TDN, % ----						
75.2	76.8	75.5	0.6	0.1808	0.9341	0.3136

[1] Treatment: A = black walnut silvopasture; B = honeylocust silvopasture; C = control (open pasture)

Table 5.5. Pod productivity in honeylocust silvopasture.

	Yield		Residual		Disappearance	
Period	Mean	SD	Mean	SD	Mean	SD
	------------------- kg · ha^{-1} -------------------					
1	3930	2880	4280	3700	-350	1910
2	2970	2360	2440	1880	530	920
3	4390	2890	5770	4640	-1380	2410
4	6170	3200				
Average	4370	2830	4160	3410	-400	1750

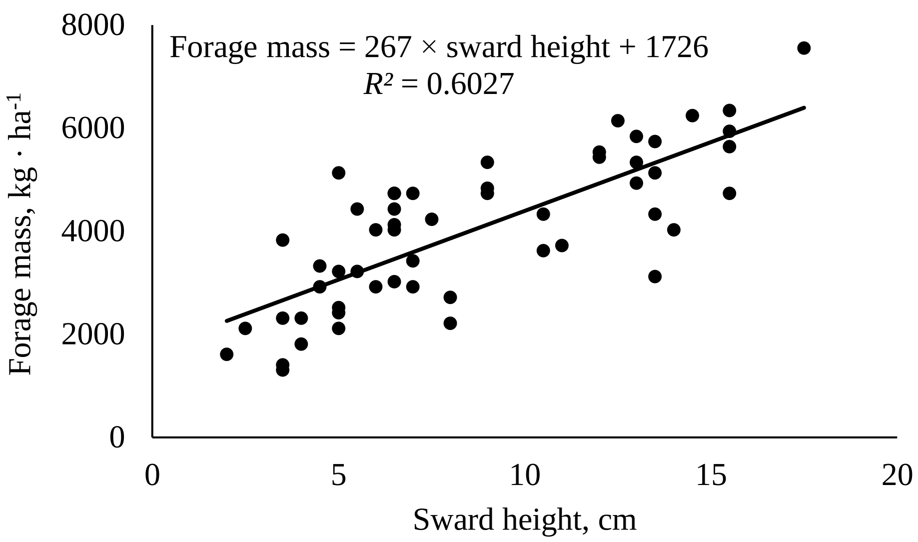


Figure 5.1. Regression of forage mass against height of sward.

Figure 5.2. Lambs foraging on a pile of honeylocust pods on December 14, 2015.

Figure 5.3. Lamb manure containing seeds from digested honeylocust pods.

Chapter 6: Conclusions

In addition to the products and environmental services provided by trees in silvopastures, animal welfare may be improved through the provision of shade. Though other studies have shown the positive impact of shade on animal productivity in intensive, confinement operations, the necessity of shade in extensive, pasture situations is not well understood. Necessity of shade for livestock should not be defined merely by apparent productivity as heat may negatively affect animal comfort and behavior prior to any noticeable decline in productivity. The objective of this study was to document not only the productivity of silvopastures, but also the benefits provided by the trees to sheep comfort and behavior.

Losses in forage productivity in the black walnut silvopastures were not tied to losses in animal productivity. In this study, black walnut and honeylocust silvopastures systems supported equivalent lamb live weight gains compared to the treeless pastures during three summers. In the case of the black walnut silvopasture, this occurred despite reductions in forage productivity of about 30% compared to open pastures and despite the presence of some less desirable forage species in these systems compared to the other systems. In the case of the honeylocust silvopastures, there were slight benefits to forage productivity and nutrition (greater N and lower NDF concentrations). It is clear that forage characteristics are not the only factors driving animal performance, particularly in the black walnut silvopastures.

The benefits to animal comfort provided by the trees in these silvopastures likely compensated for any changes in forage characteristics. Lambs in silvopastures were found to actively follow and utilize shade from the trees. In addition, the lambs in the silvopastures spent more time lying down than lambs in the open pastures. Lambs in the open pastures spent more than two hours longer each day standing up compared to lambs in the silvopastures, indicating the level of discomfort experienced by lambs without shade. No differences were found in daily bite counts and bite count by time of day for the lambs in the three systems, though lambs in the black walnut silvopastures spent slightly more time grazing than lambs in the other systems as measured from the time lapse imagery. It is not clear whether this is due to a lower forage sward where lambs may have had to compensate for less intake per bite with more time spent grazing or due to more comfortable conditions which may have been more conducive for increased grazing activity. Lambs in the silvopastures grazed more frequently and more evenly throughout the midday hours compared to the lambs in the open pastures, except in the honeylocust silvopasture in the final year. A hair sheep breed was used in the final year, which are generally more heat tolerant than wool sheep. It is likely that the increased heat tolerance of these sheep blurred the distinction in grazing behavior between lambs in the honeylocust silvopastures and the open pastures.

Although it is clear that livestock prefer shade and actively seek it, it is not clear what effect shade has on animal body temperatures in silvopastures. In this study of lamb vaginal temperatures in open pastures and silvopastures, the shade of the black walnut trees kept lambs in these silvopastures 0.4 °C cooler during the hottest parts of the day (1300 to 1700 h). However, the lambs in the honeylocust silvopastures had similar vaginal temperatures, and in one month hotter peak temperatures (August), than lambs in the open pastures. The reason for this is not clear, although it may be tied to declining shade cover provided by these trees over the growing season or to more nutritious forage consumption by the lambs in these systems. Nevertheless, both tree species modulated the impact of ambient conditions on lamb vaginal temperatures. The effect of the honeylocust trees was smaller than the effect of the black walnut trees. The variable effect of tree species on animal physiology may be an important consideration for producers designing silvopasture systems.

In addition to the summer studies, forage characteristics, honeylocust pod productivity, and lamb performance was studied during one winter. The net biomass production of the honeylocust silvopastures, in terms of forage and pods, exceeded the production of the open pastures during this study. Unfortunately the lambs were initially unfamiliar with pods and did not begin consuming pods until four weeks into this six week study. During this final period, the weight gains of lambs in the honeylocust silvopastures were greater than the weight gains of lambs in the open pastures but not the black walnut silvopastures. This short study documented the overyielding potential of honeylocust-based silvopastures towards net primary productivity, and these data suggest that live weight gains of sheep may be increased when honeylocust pods are consumed in combination with cool-season forages by growing lambs. Future studies should account for the training time necessary to introduce honeylocust pods as a fodder source to specific ruminant species.

Even with the potential products and ecosystem services rendered by the trees in these silvopastures, these systems had similar animal output compared to the conventional open pastures during the summer months and during one winter study. In addition, these silvopastures sheltered the lambs from ambient summertime conditions, leading to improved animal welfare compared to open pastures. Future studies should examine the year-round productivity and animal gain efficiency of these systems, as well as the ecosystem services provided by these systems compared to open pastures or timber plantations. The interaction between tree species selection and spacing should be investigated to minimize losses to forage productivity and yet maximize animal welfare and environmental quality. The data collected in these studies have shown that silvopastures can increase the productivity of cool season forage-based pastures, while improving animal welfare in temperate regions during summer months.

Chapter 7: References

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