EVALUATING THE RELATIONSHIP BETWEEN TIMBER AND FORAGE YIELDS IN A LOBLOLLY PINE-SWITCHGRASS SILVOPASTORAL SYSTEM

By

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Executive Summary

As forest and agricultural landowners look to increase revenue streams and diversify risk, agroforestry systems could be viable land use options. Silvopasture is an agroforestry system that integrates the production of timber and livestock. With careful planning, a silvopastoral system can be designed in which landowners can meet their objectives, obtaining substantial yields from both products. In addition, the integration of both systems can help landowners diversify their financial risks.

Silvopasture is practiced globally and has great potential in the US South. Implementation of silvopastoral systems can vary, depending on landowner objectives. Two species with potential in the US South for such a system are pine (timber) and switchgrass (forage). Managing for both silvopasture products presents establishment challenges and requires a nuanced understanding of how tree growth will affect forage yields over time. This report explores the relationship between loblolly and switchgrass, planted in an alley cropping system, where rows of timber are planted adjacent to alleyways of forage. The report focuses on how dominant tree height, the width of timber rows, leaf area index, and the directional orientation of the system affect forage yields.

This study was carried out in collaboration with the Caldwell-Dietzel Farms (CDF). The Caldwell-Dietzel Farms is a family owned and managed farm located in Robeson County, NC. At the time of this report, the CDF have 172 hectares in timber production, managed for loblolly, longleaf, and non-timber forest products such as pine straw. Their management goals include investment for future generations, increasing periodic income, and diversifying holdings and management. Silvopasture was identified as an alternative land use practice that might meet their needs.

Timber stand development in the alley cropping systems was modeled over a 35-year rotation using LobDSS, an expert system with an integrated whole stand growth and yield model (FastLob3.1, Virginia Tech Forest Modeling Research Cooperative). The model setup included a planting density of 681 trees per acre and thinning operations at years 14 and 25. Biomass outputs from LobDSS were also used to estimate leaf area index. Forage yields were modeled using switchgrass biomass growth model from Albaugh et. al (2014) that was combined with a radiative transfer model to account for the reduction in production due to shading from the tree corridors. The amount of solar energy available to support forage growth across the alleyway was modeled based on the amount of incoming solar radiation, distance from the tree corridor, tree corridor width, dominant tree height, and leaf area index within the tree corridor.

The alley cropping design was modeled facing in four directional orientations: east-west, north-south, northeast-southwest, and northwest-southeast. The tree corridors were modeled in widths of 2, 3, 4 and 5 trees wide adjacent to alleyways of 12, 19, 24, and 30 m wide. Forage yield was also modeled for a silvopasture system without alleys of forage. Using similar planting densities to the alley cropping scenarios, this savanna scenario modeled grass growing in and among trees that were evenly spaced across the area.

Results of this study suggest an alley cropping system aligned in an East-West orientation yields the greatest amount of forage in all tree row width-forage alley combinations. Forage yields from all alley cropping systems are considerably higher compared to savanna systems. As tree height,

leaf area, corridor width and, thereby, shading on the alleys increase forage production decreases. This decrease can be reversed through thinning. In the East-West orientation, the greatest effect of timber on forage yield occurs within the first five meters of the forage alley. With saturation occurring after the 10th forage meter, wider forage corridors can compensate for losses incurred in the first few meters.

The behavior of timber and livestock as financial assets were compared using a financial analysis. Using modern portfolio theory and correlation analysis, it was determined that these two assets behave different financially in terms of the volatility of their returns relative to the greater market. Because these two assets are subject to different market forces, pairing the two assets on one tract of land might provide landowners with an opportunity to diversify financial risk. In addition, the two assets produce revenue in different intervals. Revenue generating events occur more periodically for livestock. Integrating livestock with a long-term yield product like timber can also diversify cash flow.

These results on the interaction between forage and timber yields coupled with a further financial analysis can provide guidance to landowners interested in exploring silvopasture as a land use option. Understanding how management can improve conditions over time can also help landowners design a system suitable to their land base.

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Introduction

Private forest landowners face a variety of pressures and challenges to keep their land forested. In response, private landowners are exploring alternative land uses, like agroforestry, to diversify risk and increase revenue (Workman & Allen 2003). Additionally, private landowners are increasingly interested in sustainable land use practices that are economically viable (Buck 1999). Benefits of agroforestry range from economic to environmental services, including but not limited to enhanced soil fertility, carbon sequestration, improved water quality, and enhanced aesthetic values (Shibu 2009). One potential agroforestry practice with ability to meet the needs of landowners is silvopasture.

Silvopasture, the most common agroforestry practice in North America, is defined as the management of forage, livestock, and trees (Orefice & Carroll, 2017; Udawatta, R. & Jose, S. 2012). As an integrated land use, silvopastoral systems can reduce financial risk through diversification, increase revenue streams in the short term, and maintain long term timber production (Workman & Allen 2003). Implementation of silvopastoral systems varies throughout the globe, incorporating trees for mast and forage production, shade, or high-quality timber (Cubbage et al. 2012). In the US South, silvopastoral systems are typically designed with a component of production forestry, providing yields from timber in the long term and cattle in the short term (Ares et al. 2003).

Silvopasture can be a profitable alternative to traditional forest management. The multiple products of this integrated land use system can diversify revenue and possibly enhance cattle or forestry operations (Nowak et al. 2002), providing advantages for both industrial and nonindustrial woodland owners. Clason (1998) argues that industrial forestry plantations can produce sustainable amounts of forage in stands managed for sawtimber, and that allows silvopasture to be a profitable endeavor. This risk mitigation through diversified revenue streams can be appealing to non-industrial private landowners as they seek alternative means of addressing ownership challenges (Buck 1999). For non-industrial private landowners, silvopasture generates revenue for landowners outside of the traditional timber revenue generating events, mid-rotation thinning and final harvest. To achieve the desired goal of economic viability, system design and implementation are of utmost importance.

In the Southeastern US, silvopasture typically integrates cattle with southern yellow pine trees and warm and cool-season grasses (Cubbage et al. 2012). Silvopastoral systems are most commonly established in old pastures, but systems can also be established in existing timber stands through stand management (i.e. thinning) or clearcutting with replanting both forage and trees (Tian et al. 2016). Planting arrangements can vary within a Southeastern silvopastoral system, but most commonly, landowners implement an intercropping system, planting pine tree rows adjacent to alleyways of forage (Cubbage et al. 2011). Rows of trees are commonly spaced by 20 ft alleyways of grass (Husak and Grado 2002), but forage alleyways are also planted up to 40 ft in width (Nowak et al. 2002).

Understanding relationships between system components is vital to designing an appropriate and successful alley cropping silvopastoral system. Silvopasture systems require intentional design and intensive management in order to synthesize and integrate the biological and physical interactions between timber and forage (Chizmar et al 2018). A wide range of warm and cool season grasses can be used for alley cropping within a silvopastoral system (Kephart et al. 1992). When establishing in a mature timber stand, cool season grasses, which are more productive than warm season grasses in lower light environments, might be more ideal (Clauson & Robinson 2000). Warm season grasses present establishment challenges which suggest establishing an alley cropping system in an existing pasture might be more advantageous (Albaugh et al. 2012; Wolf et al. 1992). These establishment challenges can be mitigated by using fertilizer which can positively influence timber yields (Wolf et al. 1992).

One crop with potential is a switchgrass-monoculture within the forage alleyway. Switchgrass (Panicum virgatum L.) is a C4 (warm season) grass, which has a higher optimum photosynthetic temperature than other types of grasses (Kephart et al. 1992). This high optimum temperature could prove advantageous in the US South's hot summer growing season. Other advantages of switchgrass include a low nutrient demand, its perennial nature, a high biomass potential, and the potential for significant belowground carbon sequestration. (Albaugh et al. 2014). Switchgrass can provide cattle high nutritional value in the early season (Richner et al. 2014). Switchgrass has also been proven to be palatable forage which can be lightly grazed a second time each season with favorable growing conditions (Anderson 2019).

The spatial arrangement of the alley cropping system allows for the intensive management of timber adjacent to the intensive management of forage. This separate yet integrated system can benefit both timber and forage production but must be balanced due to resource competition. Tree rows adjacent to improved pastures in alley cropping systems have produced greater tree diameters at breast height (DBH) and total tree height than in systems with random tree distribution (Ares et al. 2003). In addition to increased timber yields, Cubbage et al. 2012 argue that an intercropping system will produce high tree survival rates while providing alleyways of radiation for forage production. While these positive benefits are a result of the alley cropping system, competition for resources, such as water, sunlight, and other nutrients, should be considered (Burner & Belesky 2008). The design of an alley cropping silvopasture system must balance this competition to obtain the benefit potential.

Some literature investigating the effects of tree density and age on switchgrass establishment and production demonstrated successful switchgrass establishment after thinning mature loblolly pine stands (Blazier et al. 2012). Increased forage yields have been found with increased spacing between trees (Burner and Brauer 2003). Forage biomass productivity also has been found to be directly correlated to its distance away from the tree rows (Tian et al 2016). As tree height increases, forage production decreases in the alleyways due to reduced amounts of photosynthetically active radiation (PAR) (Albaugh et al. 2014). The literature describes forage yields decreasing with increased tree densities and age, suggesting a larger alleyway of forage might be necessary to maintain greater sun exposure throughout the timber rotation (Blazier et al. 2012).

This study focuses on evaluating the suitability of various alley cropping arrangements for the family owned and managed Caldwell-Deitzel Farm. The family desires to acquire and aggregate tracts to rebuild the farm's holdings to its former size. Once a 405-hectare (1,000 acre) farm, it must consider more diverse land use activities in order to make acquisitions financially viable. The family has been converting cropland into timber production and has acquired new acreage in recent years. The family's objectives include investigating innovative and ecologically sound management, diversifying risk, increasing short term revenue, and maintaining long term timber yields.

This analysis modeled loblolly pine (Pinus taeda) in the silvopasture system. Loblolly pine was selected as the timber species because it was established as the species of choice by the Caldwell-Deitzel Farm. The USDA also recommends loblolly pine because of its fast growth, commercial value, and the availability of improved genetics that can reduce rotation lengths (Hamilton, 2008).

In addition to investigating these biological relationships, this study explored financial implications of implementing silvopasture. The application of silvopasture has the potential to diversify financial risk by creating two separate products from the land. In addition, timber and cattle return revenue at different frequencies, a possible benefit for woodland owners. In the Southeast, silvopasture has a method that has been proven to be effective and financially viable, but Bruck et al. (2019) contends that intensive pine management alone is more profitable than silvopasture. The extent of profitability will largely depend on highly variable markets and careful design and execution of the silvopasture system in terms of its cattle and timber productivity. Through increased study and analysis, the current silvopasture practices and systems (the spatial distribution of trees and forage) can be improved to optimize yields for both timber and livestock, making it more competitive with intensively managed monoculture systems (pine monoculture and livestock monoculture).

The objective of this analysis is to determine how changes in spatial arrangements of a silvopasture system affect biological productivity of both timber and forage. As trees grow taller, how will the increased shade affect forage production? This analysis will also examine the effect of increasing the width of tree rows adjacent to the forage alleyways. How will the addition of one tree to the width of the tree row affect forage production? Finally, we will investigate the system's relationship with cardinal direction, rotating the system's orientation to determine how azimuth orientation affects forage productivity. Results from this analysis will help determine if a silvopasture system can achieve financial viability and prove economically competitive. The analysis will provide insight into optimal alleyway widths and tree planting densities, allowing landowners, like the Caldwell-Deitzel Farm, to reasonably evaluate returns over the life of a timber rotation based on their objectives.

Methods

Study Site

The study site is located three miles northwest of Lumberton, NC in central Robeson County (34° 39.37’ N, 79° 02.33’ W). The site is owned by the Caldwell-Deitzel Farm and managed by Walter Thomas of Forest Land Resource Consultants. The tract is referred to as the RH Stephens tract. The entire tract is 11.7 ha (29 acre), but for this study, only 5.3 ha (13 acres) are being examined. These acres were chosen because of their age (18 years old) and the stand composition. The study site was an old agricultural field that was planted with loblolly pine. With no management, the site also experienced volunteer growth from natural seeding of loblolly pine. The Caldwell-Deitzel Farm recently acquired the property and began implementing stewardship management activities in 2017. In 2017, the site was thinned, and in 2019, the site was burned through a prescribed fire. The site currently has 1047 trees per hectare (424 trees per acre), and the overstory is composed of loblolly pine. The stand dominant height is 17.9 m (59 ft), and the diameters range from 10-30 cm (4-12 inches). The pine basal area is 26.4 m^2/ha (115 ft^2/acre). A majority of the standing timber is of pulpwood quality, with little sawtimber currently present. Understory hardwood species consist of sweetgum and black cherry. Goldsboro loamy sand is the dominant soil type with 0-2% slopes (Soil Survey Staff). Lynchburg sandy loam and Norfolk loamy sand are also present in small quantities (Soil Survey Staff). These soil types are moderately well-drained (Soil Survey Staff). Site indices range from 25.6 m (84 ft) (Norfolk sandy loam) to 26.8 m (88 ft) (Goldsboro loamy sand) at base age 50 (Soil Survey Staff).

Site Index

Site productivity is commonly defined by site index (SI). Soil data was used to calibrate the timber growth and yield model to the RH Stephens tract location and a specific SI. According to the Web Soil Survey, the site index for loblolly pine in Goldsboro sandy loam soil is 26.8 m at a base age 50 (Soil Survey Staff). However, the growth and yield model uses a site index at base age 25. To derive a site-specific site index at base age 25, equation 1 was used (Bailey & Clutter 1974) with parameter estimates for this equation from Cao (1993). Dominant height at the time of observation was used as a parameter in the height equation [1]. Field data were used as inputs to create a more location specific site index, which determined SI_{25} = 19.9 m. The forage model was based on parameters and assumptions from Albaugh et. al (2014) whose study site was of similar quality (SI_{25} = 21.3 m).

$$H_2 = e^{\{b_1+[\ln(H_1 - b_1)]*\left(\frac{A_2}{A_1}\right)^{b_2}\}} \qquad (1)$$

Where: A_1 = age (years) at observation
A_2 = age (years) at desired
H_1 = stand dominant height (feet) at observation age
H_2 = stand dominant height (feet) at desired age
b_1, b_2 = parameter estimates

Table 1. Parameters used in height equation [1]. Field data collection supplied inputs to paramters A_1 and H_1 .

A_1	A_2	H_1	H_2	b_1	b_2
18	25	59	25	4.98114	-0.36399

Field Data Collection

Data were collected from the 5.3 ha of the RH Stephens tract on September 1, 2019. Using a stratified sample design, 15 10th acre plots (11.4 m radius) were established along transects. Diameters were measured for all trees. Total heights and crown ratios were recorded for 5 trees per plot. In plots containing a hardwood component, total height and crown ratio were also recorded. The height and crown ratio measurements are used to calibrate growth and yield models to the study site growing conditions. Merchantable heights were only recorded for saw timber trees to calibrate the Forest Vegetation Simulator (FVS) merchantable yield outputs.

Timber Models

Using the study site soil information, LobDSS was used to simulate stand development (Amateis et al. 2001). LobDSS is an expert system with an integrated whole stand growth and yield model (FastLob3.1). This study used stocking density, site index (SI_{25}), and management treatments (thinning) as the model parameters for LobDSS. For the purposes of this analysis, it is assumed the landowner would either convert an old pasture or clearcut the current stand, replanting under plantation conditions. All timber scenarios were modeled using LobDSS. The alley cropping silviculture scenarios used a 2.4 m x 2.4 m (8 ft x 8 ft) tree spacing (1,683 trees per hectare or 681 trees per acre). The stand simulation implemented two thinning treatments when the stand's basal area approached 28 m^2/ha (120 ft^2/acre). After modeling a thinning operation, timber removals were calculated from LobDSS outputs of pulpwood, chip-n-saw (CNS), and saw timber tonnage. These metrics were also evaluated at year 35 at which point the stand would be harvested and replanted. Other timber scenarios with different TPha densities, including the all-timber scenario and the silvopasture with timber and forage distributed throughout the hectare, were also modeled using LobDSS. LobDSS outputs were also used leaf area index (LAI) estimates. These outputs include biomass in Mg/ha from the stem, branches, coarse roots, fine roots, and both cohorts of foliage.

LAI Estimation

Leaf area index (LAI) was derived from biomass produced from the LobDSS model. Albaugh et. al (1998) provides an equation for LAI using the sum of foliage biomass and biomass from stem wood, branch, coarse root, and fine root growth (equation [2]). Because crown width increases with increased tree spacing (Sharma et al. 2002), it is assumed the crown width for trees along the forage alleyway will be greater than those grown in interior rows. To account for the expected increased canopy width (and resulting increase in foliage) due to the field edge effect, foliage biomass estimates from both growth cohorts were used. This assumption will also simulate peak foliage.

In years immediately following thinning operations, equation [2] produces a negative LAI. Because a negative LAI is not realistic, the relationship between LAI and total foliage biomass was used as a proxy to determine LAI. Linear regression analysis was used in this relationship to determine a mathematical and applicable tool for calculating LAI values regardless of the management prescription.

$$LAI = \frac{biomass_{sum} - 2.33}{7.26} \quad (2)$$

Radiative Transfer Model

Compared to open field conditions, forage production in an alley cropping system is reduced due to shading from tree corridors. At a given location within an alleyway (Figures 1 and 2), the amount of photosynthetically active radiation (PAR) received over a growing season depends on the amount of incoming PAR (a function of sun's azimuth and elevation angles), distance from a tree corridor as well as orientation, dimensions (tree height, corridor width), and properties (leaf area density) of the corridor. For a given sun angle, the probability of a gap (gap fraction, p) in sun's direction, allowing PAR to penetrate through the tree corridor, can be calculated using Beer's law:

$$p = \mathrm{e}^{(-k*\mathrm{LAD}*P_{\mathrm{Length}})};\ \mathrm{PAR_x} = \mathrm{PAR_I} * p \qquad (3)$$

where k is extinction coefficient, LAD is leaf area density (LAI divided by canopy height, H), P_{Lenght} is the distance that direct beam radiation travels through a canopy volume, $\mathrm{PAR_X}$ is the amount of PAR reaching a given location x, and $\mathrm{PAR_I}$ is incoming (unshaded) PAR reaching the top of the canopy.

For the gap fraction modeling in this study, an estimate of the extinction coefficient ($k = 0.614$) was taken from Albaugh et al. (2014) (Equation 3) and azimuth and elevation angles were modeled based on Gates (1980). An hourly gap fraction was calculated from 6:00 am to 7:00 pm for 1-meter sections of the alleyway in all scenarios for 223 days during the growing season (DOY 69-292) and the daily means were averaged over the growing season. To obtain $\mathrm{PAR_X}$ for each alleyway section, the growing season mean gap fraction was multiplied by an estimate of cumulative, incoming PAR ($\mathrm{PAR_I} = 1972$ MJ m^{-2}) was taken from by Albaugh et al. (2014) who estimated incoming PAR in 2011 for one of their study sites in North Carolina.

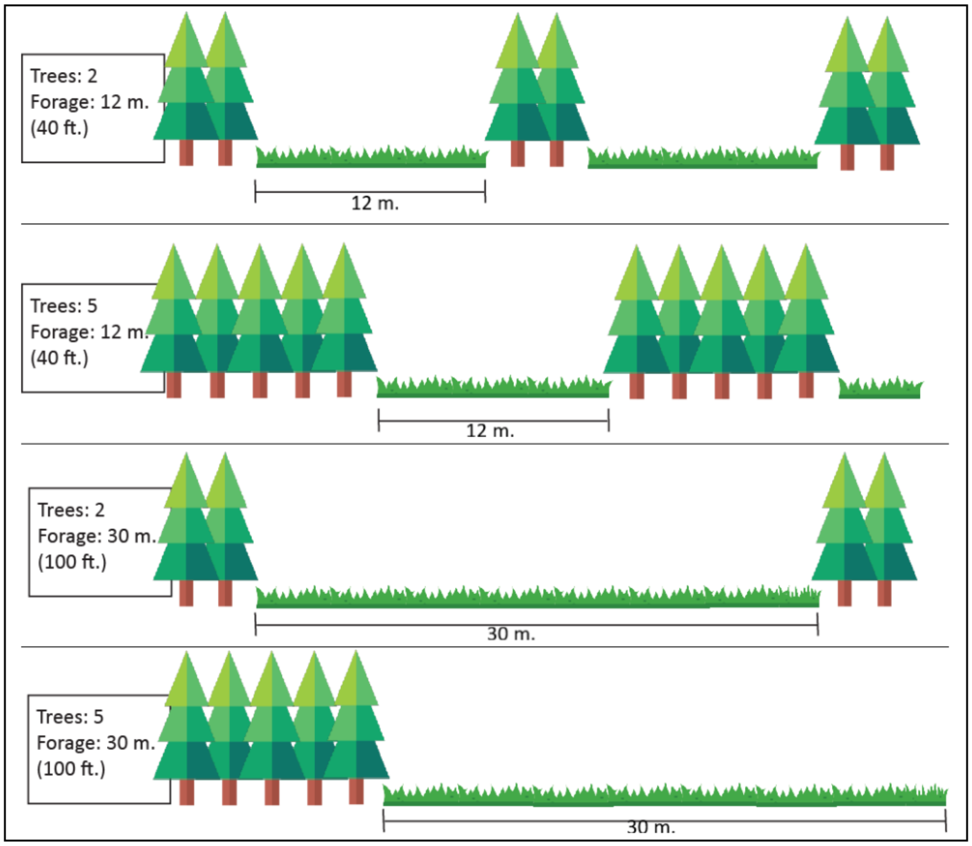

Figure 1. Two examples of alley cropping spatial arrangement. Of all scenarios modeled, the scenario with tree row of 5 and forage alley of 12 m contains the maximum amount of timber and the least amount of forage per hectare. The scenario with tree row width of 2 and forage alley of 30m contains the least amount of timber and the maximum amount of forage.

Figure 2. The increasing effect of shade on forage yields over time. Forage corridor and shadow lengths are not drawn to scale.

Forage

Forage was modeled using switchgrass biomass equations from Albaugh et. al (2014). Equation [4] uses PAR outputs from the radiative transfer model. Albaugh et al. (2014) estimated the maximum biomass at 5.2 Mg/ha (variable *c*), the value of the inflection point (parameter *b*) at 867.2 and the daily rate of switchgrass biomass accumulation (parameter a) at 0.00539. This model produces an annual forage biomass production in each square meter for the forage alleyway.

$$Biomass_{forage} = \frac{c}{1+e^{[-a*(x-b)]}} \quad (4)$$

Where: a = daily rate of biomass accumulation
b = inflection point
c = asymptote
x = PAR

Scenarios and spatial arrangements

All scenarios were modeled on a per hectare basis. Silvopasture scenarios were modeled with rows of trees that are planted adjacent to forage alleys. Row refers to the number of trees planted within the width of the tree column. The tree rows were modeled as columns of two, three, four, and five trees in width, perpendicular to the entire block of tree rows. In these scenarios, FASTLOB simulated tree spacing at 2.4 m x 2.4 m (8 ft x 8 ft). A 1.5 m (5 ft) buffer between exterior row tree base and forage establishment was included to protect trees from equipment damage. With this spacing, tree row widths were assumed to be 5.5 m, 8.0 m, 10.4 m, and 12.8 m wide. The between tree spacing arrangement was adapted from Lewis et al. (1985) who argued that a 4 ft x 8 ft spacing in double rows yielded more wood than a single row at wider spacing. The adaptation to 2.4 m x 2.4 m was made because this model examines more than just double row planting configurations. This dense spacing will hopefully provide enough timber volume to make thinning operations economically feasible.

The remaining area of the simulated hectare was in forage alleyways with widths of 12.1 m, 19.8 m, 24.3 m, and 30.5 m (40 ft, 65 ft, 80 ft and 100 ft). Each tree row width was modeled adjacent to each forage alley width (Figure 1). The system was rotated, modeling with forage alleyways situated in four directional orientations: East-West, SE-NW, N-S, and SW-NE.

The silvopasture scenarios were adapted from an all-timber scenario modeled using FASTLOB with the 2.4 m x 2.4 m spacing parameter (1,683 trees per hectare or 681 trees per acre). This model was then modified based on the percent of an acre occupied by the area of timber (Table 1). The percent of timber per acre present was used to derive timber production in each scenario. This method of determining timber production was used because FASTLOB is not a distance dependent model. If timber was to be modeled at lower densities, growth, form, and yields would not be representative of a 2.4 m x 2.4 m spacing.

Silvopasture scenarios were also modeled without alley cropping planting densities were determined by range of densities in the directionally oriented silvopasture scenarios (Table 3). These non-alley cropping spatial arrangements resemble a pine savanna, which is more common for longleaf than loblolly pine. The solar modeling in these scenarios assumes that the canopy is horizontally homogenous. This assumption simplifies the modeling in these scenarios by assuming a random distribution of leaves throughout the canopy, whereby the average PAR under the canopy is the same at any given point. This assumption does not account for the different foliage densities across the canopy nor does it account for any open spaces or voids in the canopy. This model assumes a mean LAI throughout the stand, averaging the over and under-estimations across the canopy.

Financial analysis

To gain insight into the financial implications for landowners, the pricing behavior of the timber and livestock products considered in this study was compared to that of the market. For this analysis, the variation of returns or volatility of timber and livestock were calculated using a beta coefficient (β) that was based on 10-year timber pricing, and livestock futures data, and the S&P 500 (investing.com, 2020; Brandon, 2019). Using the resulting β values, the capital asset pricing model (CAPM) was used to determine risk-adjusted expected rates of return for both timber and cattle. The resulting expected returns were used to examine each product's performance in comparison to the equity market. To compare the pricing behavior of timber and cattle to each other, a Pearson Correlation Coefficient was determined.

Results

Forage

Forage yields are driven by light availability. In this study, modeling examined how light availability was affected by dominant tree height, leaf area index (LAI), and tree row width. Tree row width and dominant tree height increased LAI by increasing the travel distance of light through the canopy. Increasing any of these three variables decreased the gap fraction and the resulting PAR and forage productivity.

As predicted, forage yields and productivity increased as the distance from the tree row increased (Figure 3). Each meter of forage away from the tree row, moving into the forage alley, increased the average gap fraction by reducing the amount of time in which that meter of forage is directly influenced by shade. Increasing tree heights increased the time under which an area is in shade (Figure 4a and 4b). These factors and the different light beam path lengths created different shade intensities, which in this study are represented by the gap fraction.

Increasing tree row width also decreased gap fraction and resulting forage productivity. In wider tree row scenarios, growth followed a similar pattern, but the first few meters were more affected by the increased tree row width. In the first meter, the 2-tree row produced an average annual gap fraction of 0.43 and an average of 2.5 Mg/ha of forage biomass. By comparison, the 5-tree row produced a gap fraction of 0.37 and an average of 1.6 Mg/ha of forage (differenced of 0.06 and 0.87 Mg/ha). Saturation occurred by the 10th meter of forage. In the 5th meter of forage, the differences in average annual gap fraction was 0.04 and in forage biomass was 0.31 Mg/ha. By the

10th meter of forage. The average annual differences had reduced to 0.02 and 0.06 Mg/ha. Beyond the 10th meter, tree row width had insignificant influence on forage productivity.

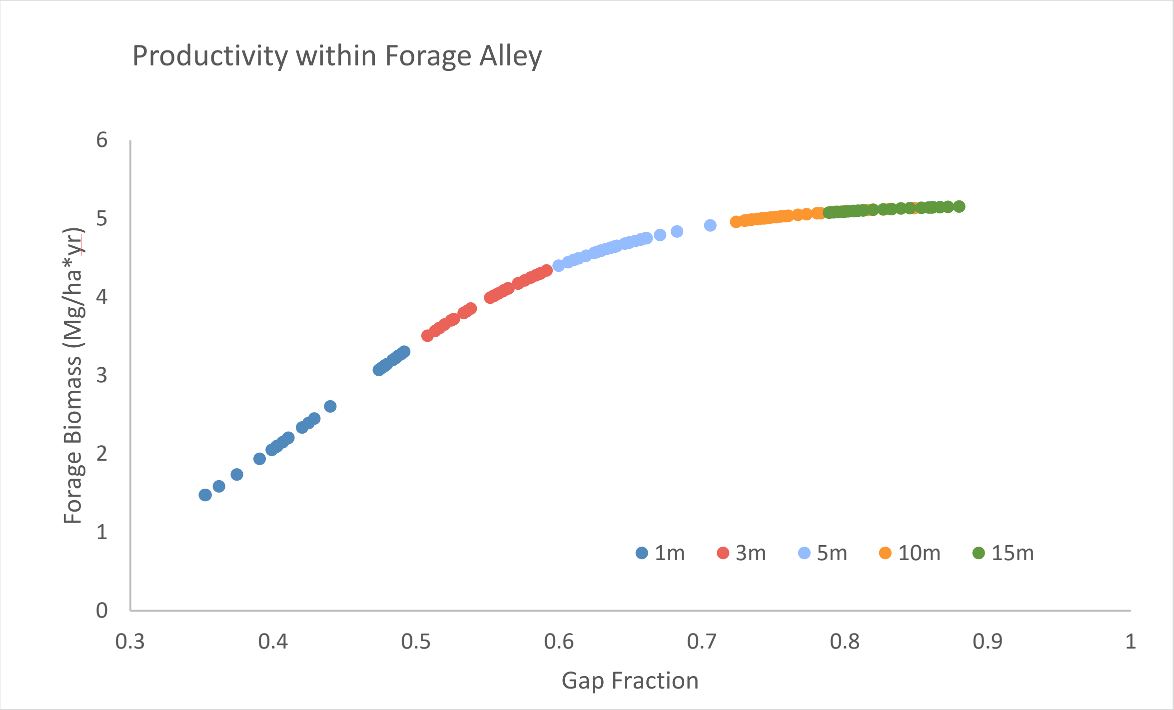

Figure 3. Forage productivity by meter within the forage alleyway. Each meter represents a square meter at specified distances from the southern edge of the tree row in the East-West orientation scenario. Points within each meter represent average annual productivity from year 10-35. Results are from the 2 Tree Row scenario.

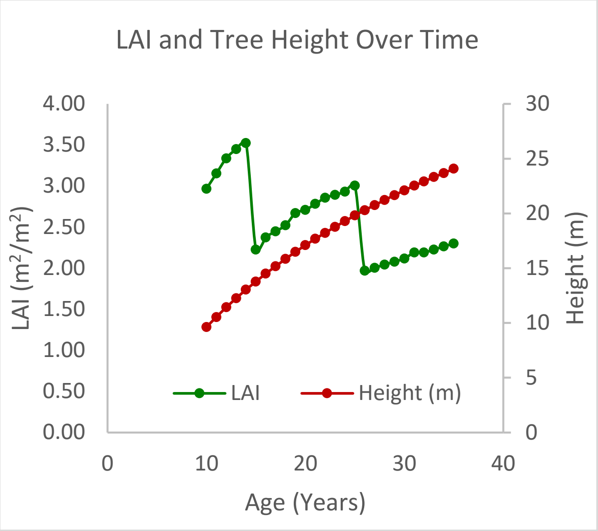

Figure 4a. LAI and height throughout rotation (Yr 10-35). Reductions in LAI occur during thinning treatments at age 14 and 25.

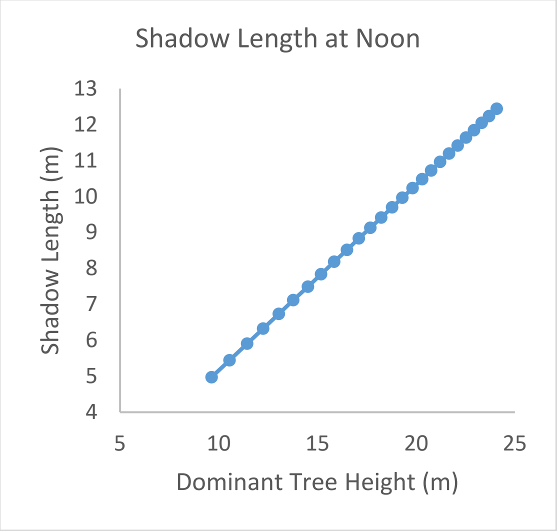

Figure 4b. Shadow length at noon as a result of increasing dominant tree height.

Increasing dominant tree height increased the area of forage that is influenced by shade (Figure 4b). Average shadow length increased from 5 m to 12.4 m over the modeling horizon. The first 5 meters of forage experience some amount of shade for the entirety of the timber rotation. LAI increased over time but was also influenced by mid-rotation treatments (Figure 4a). Thinning operations in years 14 and 25 reduced LAI. An increasing LAI reduced the average gap fraction of light penetration through the tree canopy (Figures 5a and 5).

12 m Forage Alley

Figure 5a. Average annual gap fraction in 12m forage row. With similar height and different LAI, gap fraction decreases with increasing tree row width. Results from East-West orientation.

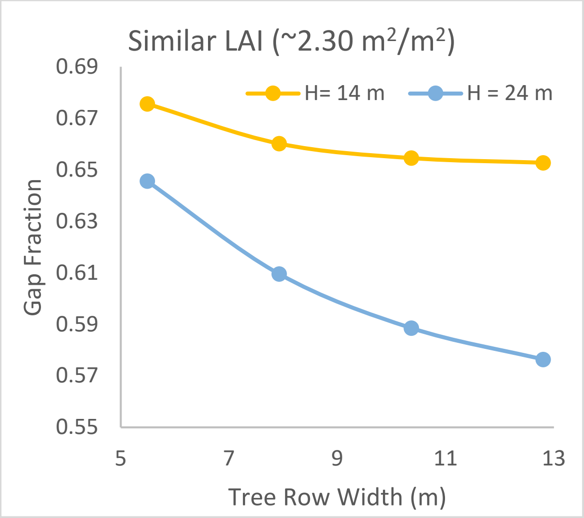

Figure 5b. Average annual gap fraction in 12m forage row. With similar LAI and different dominant tree height, gap fraction decreases with increasing tree row width. Results from East-West orientation.

The different influence of LAI and dominant tree height can be attributed to changing leaf area densities (LAD = LAI/H) (Figures 5a and 5b). In a 12 m forage alley with similar LAI, increasing tree row width compounded the influence of height by increasing the length of light travel through the canopy. In the 12 m forage alley with dissimilar LAIs but similar dominant tree heights, the difference in gap fraction remained similar across all four tree row width scenarios. In the 2-tree row scenario, gap fraction differed by 0.05, decreasing to a difference of 0.04 by the 5-tree row scenario (Figure 5b). By contrast, the influence of tree row width varied when examining scenarios of similar LAIs but different dominant tree heights. Gap fraction only differed by 0.03 in the 2-tree row (5.4 m tree row width). This difference more than doubled to 0.08 in the 5-tree row scenario (12.8 m tree row width) (Figure 5b). In narrower tree rows, tree height had more of an influence than tree row width on the length of light travel through the canopy.

To further examine the effects of LAI and dominant tree height, the gap faction calculated for each meter of forage can be explored. In this first meter of forage, the difference in gap fraction with similar tree heights and different LAIs did not change significantly across tree row widths (from 0.08 at 2 trees to 0.07 at 5 trees) (Figure 6a). In this first 1 m of forage with similar LAI in the adjacent corridor, increasing tree row width reduced the influence of height (Figure 6b). In the 2-tree row scenario with similar LAIs, gap fraction differed by 0.05, but by the 5-tree row scenario, no difference in gap fraction existed. That is, in wider tree rows, the increase in the path length through the canopy reduced the effect of tree height on the gap fraction.

The First 1 m Within the Forage Alley

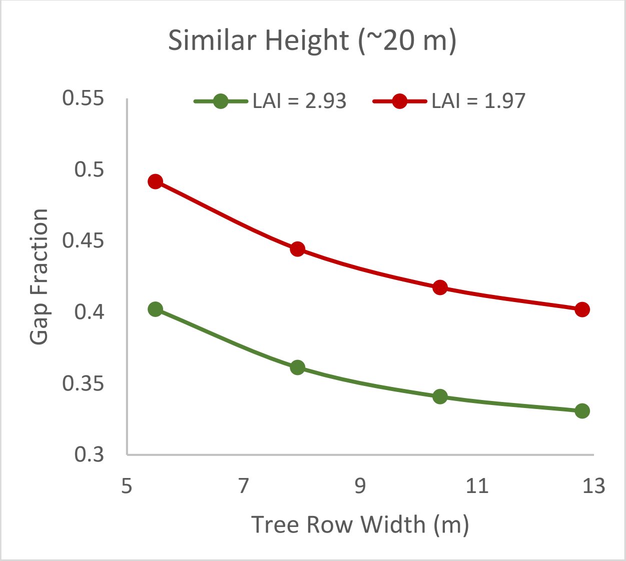

Figure 6a. Average annual gap fraction in the first 1 m of forage, adjacent to the tree row. Results from East-West orientation.

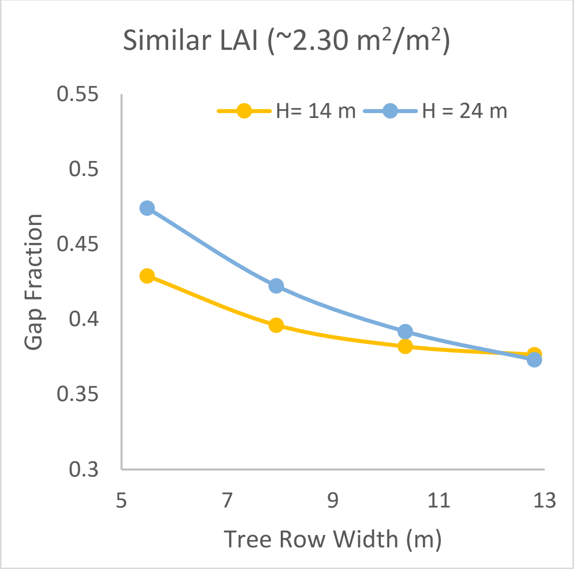

Figure 6b. Average annual gap fraction in the first 1 m of forage, adjacent to the tree row. Results from East-West orientation.

Increasing tree row width decreased gap fraction and resulting forage productivity. The concave nature of these results implies that the addition of one tree row did not linearly decrease gap fraction. Each additional tree had an accumulating effect on the gap fraction due to the model parameters. Adding a tree to the tree row width increased the width of the canopy, creating a longer light travel distance through the canopy. The model used this light travel length to determine a relative amount of light (PAR) reaching each meter of forage within the forage alley. When thinning operations were simulated, LAI was reduced across all tree row width scenarios, increasing amount of PAR reaching the alley and thus forage productivity

Without management, dominant tree height and leaf area increased over time, reducing the gap fraction in a curvilinear fashion (Figure 7a). However, this decreasing gap can be improved through management (Figure 7b). Removing timber volume through thinning reduces the LAI, which increased productivity across the entire forage alley. After thinning operations, leaf area density (LAD) decreased more than the sunlight path length through the tree canopy increased. With increasing tree row widths, the length of light traveling through the canopy was long enough to compensate for the loss in LAD, causing less point dispersion. With management, the same average gap fraction can produce difference levels of productivity (Figure 7b). This difference can be attributed to averaging the gap fraction and the distribution of the gap fraction across the forage alley at different tree heights and leaf area indexes.

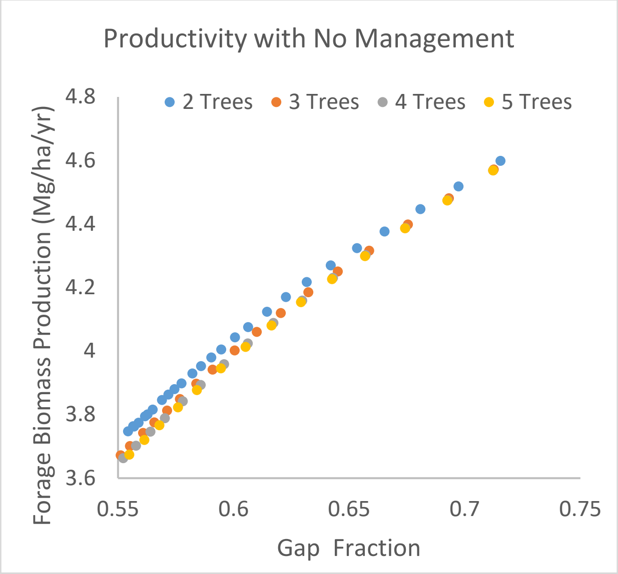

Figure 7a. Average annual forage biomass productivity in 12 m forage alley, adjacent to varying tree row widths. No management scenario in the East-West orientation.

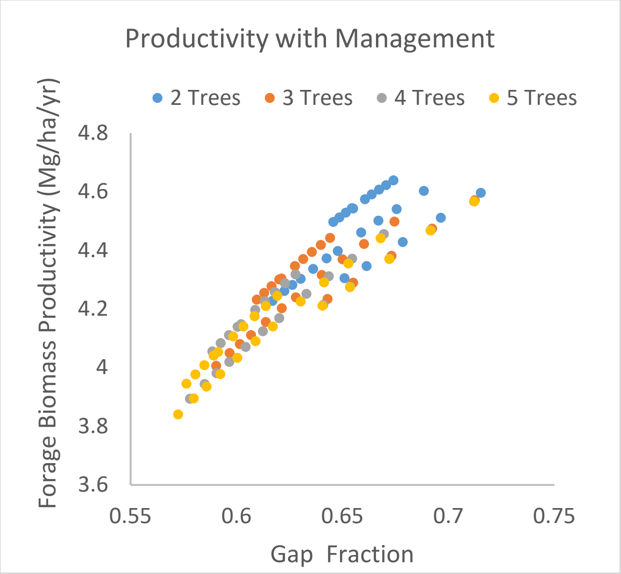

Figure 7b. Average annual forage biomass productivity in 12 m forage alley, adjacent to varying tree row widths. Each point represents mean production across the 12 m forage alleyway for each corresponding scenario of tree width. Management occurs as thinning operations in years 14 and 25. Results from East-West orientation.

All alley cropping scenarios employed the same spacing between trees which translated to a relative planting density for an entire hectare. The relative planting densities from four scenarios were modeled in a scenario that simulated timber planted throughout the entire hectare. In these scenarios, the model grew the stand as a plantation with forage growing between the tree rows. These four scenarios included the maximum and minimum available timber as well as two intermediate timber denisites.

When planting trees throughout the entire stand, forage productivity was significantly lower than in the alley cropping system (Figure 8). The scenario with the greatest opportunity for light to reach the forage was the scenario with the least amount of timber present (2-tree row, 30 m of forage, 228 TPha. In this scenario cumulative biomass was 81 Mg/ha lower than the E-W orientation of similar TPha. In the greatest amount of timber scenario (5-tree row, 12 m of forage, 820 TPha), cumulative biomass was 43 Mg/ha lower than in the E-W orientation.

Forage yields were greatly affected by the azimuth orientation of the forage alleyways. Orientation of tree and forage rows was also explored. When aligned in an E-W (90º-270º) fashion, the model predicted higher forage biomass productivity (Figure 8) across all combinations of tree row and forage alley widths. When oriented in an E-W direction, cumulative forage biomass increased by as much as 30 Mg/ha (in the 5-tree row width scenario) and as little as 15 Mg/ha (in the 2-tree row width scenario). As a result, the East-West orientation scenario was used for all previous investigation into the driving factors of biomass productivity.

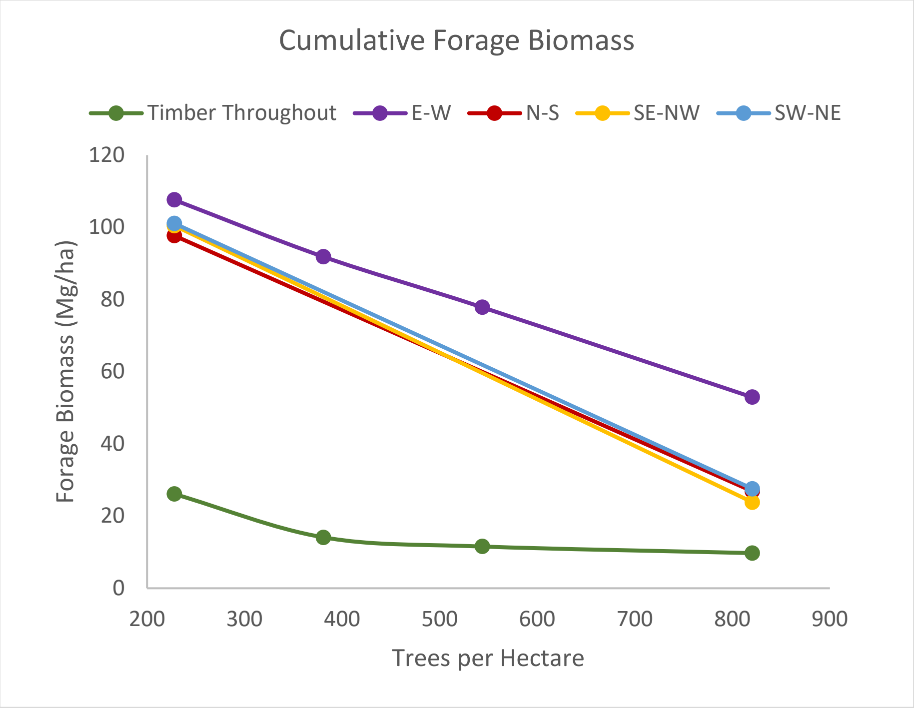

Figure 8. Cumulative biomass comparing scenarios with different forage alley orientation and the scenario with trees planted throughout the entire hectare. This figure represents scenarios with the greatest possible timber (5 tree row, 12 m of forage, 820 trees per hectare) and the least possible timber (2 tree row, 30 m of forage, 228 trees per hectare).

Timber

The alley cropping timber model produced volumes based on 1,683 TPha, planted with a 2.4 m x 2.4 m tree spacing. The results of this model were then scaled by the percentage of timber present in each scenario. The greatest increase in timber removed occurred when transitioning from the 2 to 3-tree row. In the scenario with 12 m of forage, the 3-tree row produced 5.4 more tons of pulpwood, 3.3 more tons of CNS, and 3.0 more tons of sawtimber than the 2-tre row (Figure 9). By contrast, the 4-tree row produced 3.4 more tons of pulpwood, 2.1 more tons of CNS, and 1.9 more tons of sawtimber. Total removed volume increased by as much as 12.4 m^3 when moving from the 2 to 3-tree row scenario. Timber volume removed only increased by 7.9 m^3 between the 4 and 5 tree row scenarios.

Timber volumes for the timber throughout the hectare were also derived from FASTLOB using associated planting densities (TPha for these scenarios seen in Figure 8). In these scenarios, spacing between trees ranged from 2.2 m (820 TPha) to 4.2 m (228 TPha). However, volume removals from these scenarios are not comparable to their alley cropping counter parts due to timber quality and form concerns. The potential for decreases in sawtimber quality trees due to wider tree spacings are additional reasons to forgo further exploration of these timber throughout the hectare scenarios (Amateis et. al 2002; Clark & McAlister 1998).

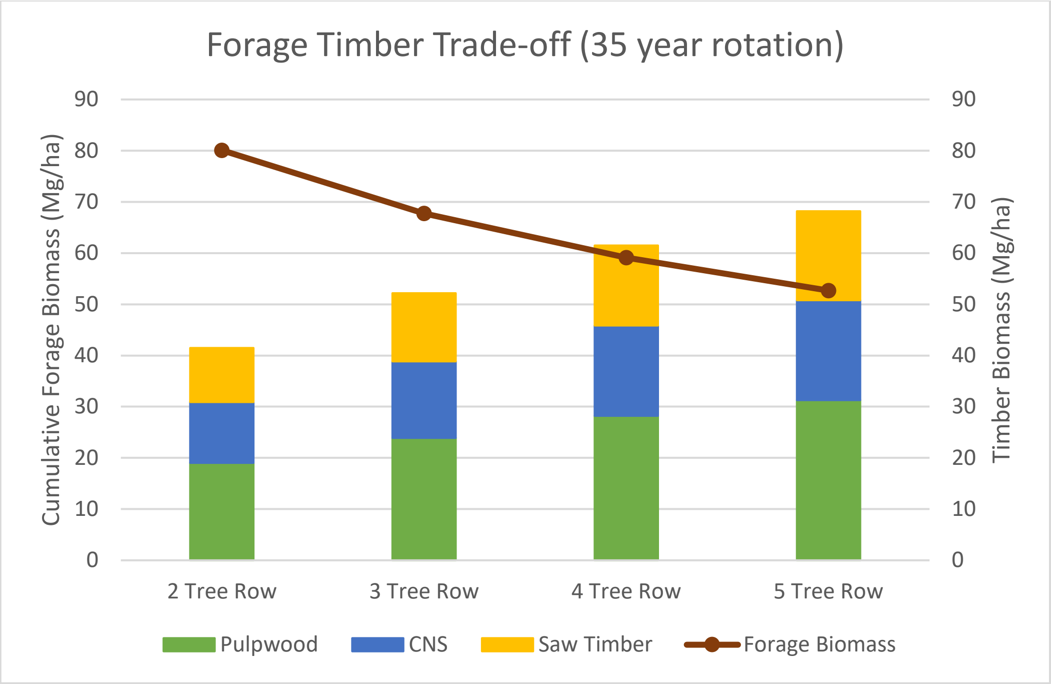

Figure 9. Cumulative forage production and timber removals by product class adjacent to 12 m forage alley. Timber removed includes both thinning operations and a final harvest.

Cattle

Using the Natural Resources Conservation Service's (NRCS) formula for evaluating how many animals can be supported by a pasture, a cattle carrying capacity was calculated for a 100 ha tract. The maximum number of animals the pasture can support was calculated by dividing average forage yield by the product of average animal weight (454 kg), grazing days (223), and the daily utilization rate for livestock (0.04) (NRCS, 2009). Over 100 hectares using the 12 m forage alley, the NRCS formula yields a range of 151 cows (5-tree row) to 163 cows (5-tree row) (Figure 10). each addition of a tree row does not linearly decrease the amount of cattle that can be supported. When comparing scenarios with similar forage alleyways, the number of supported animals does not change at the same rate as timber. With timber, volume increased almost linearly with each additional row of trees. Scaling with the decrease in forage yield, the change from 2 to 3 rows of trees incurs a greater loss in grazing capacity than when moving from 3 to 4 or 4 to 5 rows of trees. This trend is similar across all forage alley widths. With each increasing forage alley width, cumulative forage biomass increases to an extent that reduces the difference in grazing capacity.

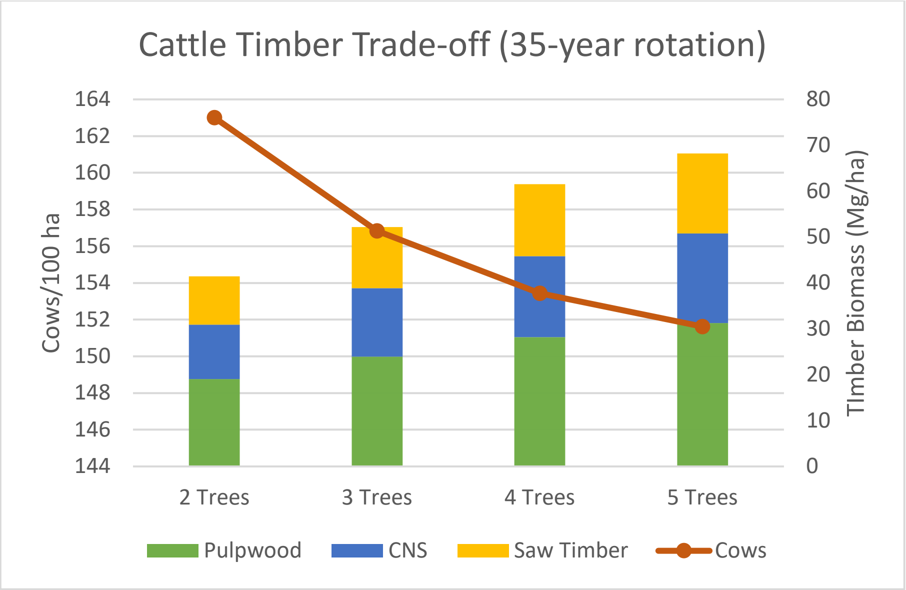

Figure 10. Cattle carrying capacity based on NRCS formula for animals supported per pasture. This figure represents yields from the 12 m forage alley.

Financial

The β coefficient for livestock and timber were 0.219 and 0.147, respectively. The risk-adjusted expected rate of returns produced by the CAPM were 2.7% for livestock and 2.0% for timber. The Pearson Correlation examines the strength of the linear relationship between variables, and the analysis produced a coefficient of 0.25.

Discussion and Conclusion

Manipulating light environments at the forest floor is a key pillar of forestry and is a crucial element when designing an intercropping agroforestry system. As tree rows increase in width, light availability in adjacent forage alleyways will decrease, which has a significant effect on switchgrass growth and productivity (Albaugh et al. 2014). Along with reduced PAR, increased shade affects the switchgrass physiology, increasing its specific leaf area (SLA) while reducing its light-use efficiency and photosynthetic capacity (Albaugh et al. 2014). Increasing tree height has a similar effect, causing greater portions of the adjacent forage alleyways to experience shade. However, we can alter the influence of these variable through management.

Mid-rotation management operations, like thinning, can arrest the decreasing gap fraction. In these models, thinning was able to boost the gap fraction by reducing the leaf area. When compared to an unmanaged stand, each thinning resulted in increased biomass productivity until the next management intervention. All four tree-row widths showed a similar change as a result of management.

The results of these management interventions were most noticeable in the 12 m forage alley due to saturation occurring after the 10th forage meter. Through averaging, wider forage alleys reduce the influence of tree-row width. Other management interventions, such as fertilization, were not modeled in this study. Fertilization of both products could have interesting implications on yields and the timing of other management decisions, like thinning. All management interventions will need to explore considerations that were outside the scope of this study. For example, land base size will have meaningful implications on the feasibility of thinning. Enough wood must be present to create an operable environment for thinning. Manipulating the spatial arrangement of the system can provide landowners with options, regardless of their land base size.

For the purposes of discussion, we will consider three landowner objectives when applying understanding of how timber yields affect switchgrass productivity. (1) The landowner wants to maximize economic returns from all assets (maximize both timber and cattle). (2) The landowner is more interested in maximizing cattle, using timber to improve grazing conditions and to provide and a longer frequency revenue source. (3) The landowner is timber focused but wants to create a more frequent source of revenue, using cattle to meet this goal and to diversify financial risk. These scenarios are an over-generalization of possibilities but could be modified to consider other landowner objectives. For example, the aesthetic value of cattle in a forest setting could be considered under the third landowner objective scenario.

Each of these landowner objectives could implement a different spatial design to best serve their specific goals. To improve grazing conditions (landowner scenario 2), lower tree-row densities will provide consistently higher levels of PAR for increased forage yields while also providing the grazing benefits of decreased heat stress and weather element shelter (Karki & Goodman 2010). In addition, this landowner could choose a spatial arrangement with lower tree density (two or three tree-rows) and wider forage alleyways, maximizing the possible AU days. Retaining high timber yields (landowner scenario 3) with greater tree-row densities will reduce forage quality but can produce enough forage to support a viable amount of cattle. The optimization of both products (landowner scenario 1) occurs somewhere between these two ends of the alley-cropping design spectrum and greatly depends on local markets and the discount rate applied by the landowner.

Understanding financial risk as it relates to timber and livestock is essential to gaining insight into the diversification silvopasture can potentially offer if considered part of a portfolio of financial assets. Private landowners often view their land as a single asset. A single asset implies a single type of product, but an interesting question is whether silvopasture creates a new paradigm in which one asset can serve as two. Implicitly, managing for timber and cattle are reasonable land uses and seem to be profitable because they are ambient land uses in Robeson County. Furthermore, landowners might consider integrating these two assets in a silvopasture system to derive a unique diversification benefit.

If we assume that a landowner views his or her land as part of a broader portfolio of financial assets, there appears to be some diversification value in silvopasture. We can use modern portfolio theory to investigate the diversification of financial risk. Financial risk is divided between unsystematic and systematic risks. Unsystematic risk is specific to an asset or industry and can be diversified (Markowitz 1952). An intensive drought year is an example of unsystematic risk for a cattle operation, which could have severe implications regarding that year's yield. On the other hand, timber yields are not adversely affected by a single year of drought. In short, the financial behavior of the two land use products appears by these measures to be distinct. By pairing timber with cattle in a single land use choice, the unsystematic risk can be diversified and hopefully partially mitigated more so than by either use alone.

By contrast, systematic risk is inherent to the market at large. The capital asset pricing model (CAPM) is one way to evaluate systematic risk. In this analysis, returns for each product were calculated relative to the equity market, using beta coefficients (β) and the CAPM. The β coefficients for both timber and livestock were below 1, meaning both products are theoretically less volatile than and less correlated with the broader market at large. The CAPM approach in this review produced a much lower expected return than the actual returns appear to be in practice(say what they are, respectively). Bruck et. al 2019 found that individually managing for timber or livestock was more profitable than silvopasture as a single land use choice. In addition, Buck et. al 2019 found that individually managing for timber produced an internal rate of return (IRR) of 8% and managing for livestock produced an IRR of 20%. There are also questions of scale given the relative fixed cost of each activity, the profitability of each, as well as their relative mix. However, because timber and livestock are subject to different market forces, a landowner might choose silvopasture to achieve a level of independent diversification as a single land use choice. Even though the expected returns from livestock might be greater, timber could provide an opportunity to diversify, given that timber is theoretically less volatile, implied by a lower β. In other words, assuming the landowner was considering their land asset as part of a broader financial portfolio, the results indicate that the landowner, depending on their financial objectives, could make a rational choice of conducting silvopasture for greater portfolio diversification.

In addition, these two products return revenue at different frequencies, and their prices fluctuate independently. In terms of price volatility, the Pearson Correlation Coefficient indicates only a slightly positive correlation between timber pricing and that of livestock. Timber generates revenue during harvest events, which in this simulation occurred with almost decadal frequency. By contrast, livestock can generate revenue annually, depending on how a landowner chooses to manage. Due to these disparate frequencies of cash flows, pricing affects each product differently. A landowner can choose when to harvest within a greater window of time in order to achieve a better price outcome, whereas livestock owners are not afforded such long time periods for harvesting. These unique cash flow timing characteristics could contribute to the potential benefit of combining timber and livestock for their financial attributes.

Integrating the biological outputs with this modest financial analysis suggest that with silvopasture, the same piece of land could financially serve landowners in multiple ways and function in their financial view as two separate assets. Without dividing large parcels for different types of intensive management, this study indicates that landowners have more options available to them by taking advantage of two assets that behave somewhat different financially through management of a single portfolio land asset in this way.

The fairly limited scope of this study limits the generalization of the results in a number of ways is model and investigation are limited in many capacities. The amount of PAR available for switchgrass was modeled based on estimates of the annual cumulative incoming PAR for one year and the mean annual gap fraction. Year-to-year variation in total incoming PAR would be relatively easy to incorporate in the current model, however, to capture forage production under highly dynamic light environments under forest canopies would require a different approach. Such an approach would include a growth model that operates at a shorter timestep and a radiative transfer model with a more detailed description of the canopy structure and the directionality of both the direct beam and diffuse components of PAR (Gates 1980). Light environments under forest canopies will vary and be significantly more dynamic than the model. Most importantly, the current model is based on the assumption that light is the only limiting resource with regards to forage productivity. The literature suggests that light has the greatest effect on forage growth is mostly driven by light availability, but access to resources like water should also be considered (Burner & Belesky 2008). A more robust model could account for multiple limiting resources to investigate the ideal environment based on the species chosen for the silvopasture system.

This study focused on loblolly pine and switchgrass, but other species could also create a complementary silvopasture system. Bruck et al. (2019) describe the advantages of longleaf in a silvopasture system when compared with traditional longleaf timber operations. In theory, the methodology from our study could be applied to other species, but the design parameters (an alley-cropping system) must remain for the model to be directly applicable. A future investigation and different model could examine a random spatial distribution of timber. A random distribution of trees would simulate implementation in a natural stand, such as a longleaf pine savanna. In addition, grazing has the potential to help restore longleaf ecosystems by improving species richness on the forest floor (Albin 2014). Similarly, the analysis could be broadened to include the different responses of warm and cool season grasses in this system, or include rotational grazing on forage paddocks, integrating both cool and warm season grasses into one system (Chizmar et al. 2018).

This investigation described risk diversification as a diversification of financial assets relative to the broader equity market. Price volatility can be dampened by pairing timber with livestock. However, it should be noted that silvopasture can also diversify and mitigate environmental risks. A well-designed silvopastoral system could help landowners adapt to climate change and potentially create an environment in which cattle greenhouse gas emissions are mitigated (Bruck et al. 2019). Other environmental considerations such as wildfire risk and carbon sequestration could be assessed to more fully understand the range of benefits provided by this type of agroforestry system.

As economic pressures continue to mount, rational private landowners will need to consider all of their land use alternatives to meet their financial objectives. Silvopasture has the potential to meet these economic needs while providing other values to landowners. Depending on landowner goals and objectives, different spatial configurations of silvopasture systems can be suitable. This investigation explored the use of an alley cropping system, pairing switchgrass with loblolly pine. While timber growth does suppress forage productivity, a balance between the two products can be achieved, producing a viable quantity of both timber and forage.

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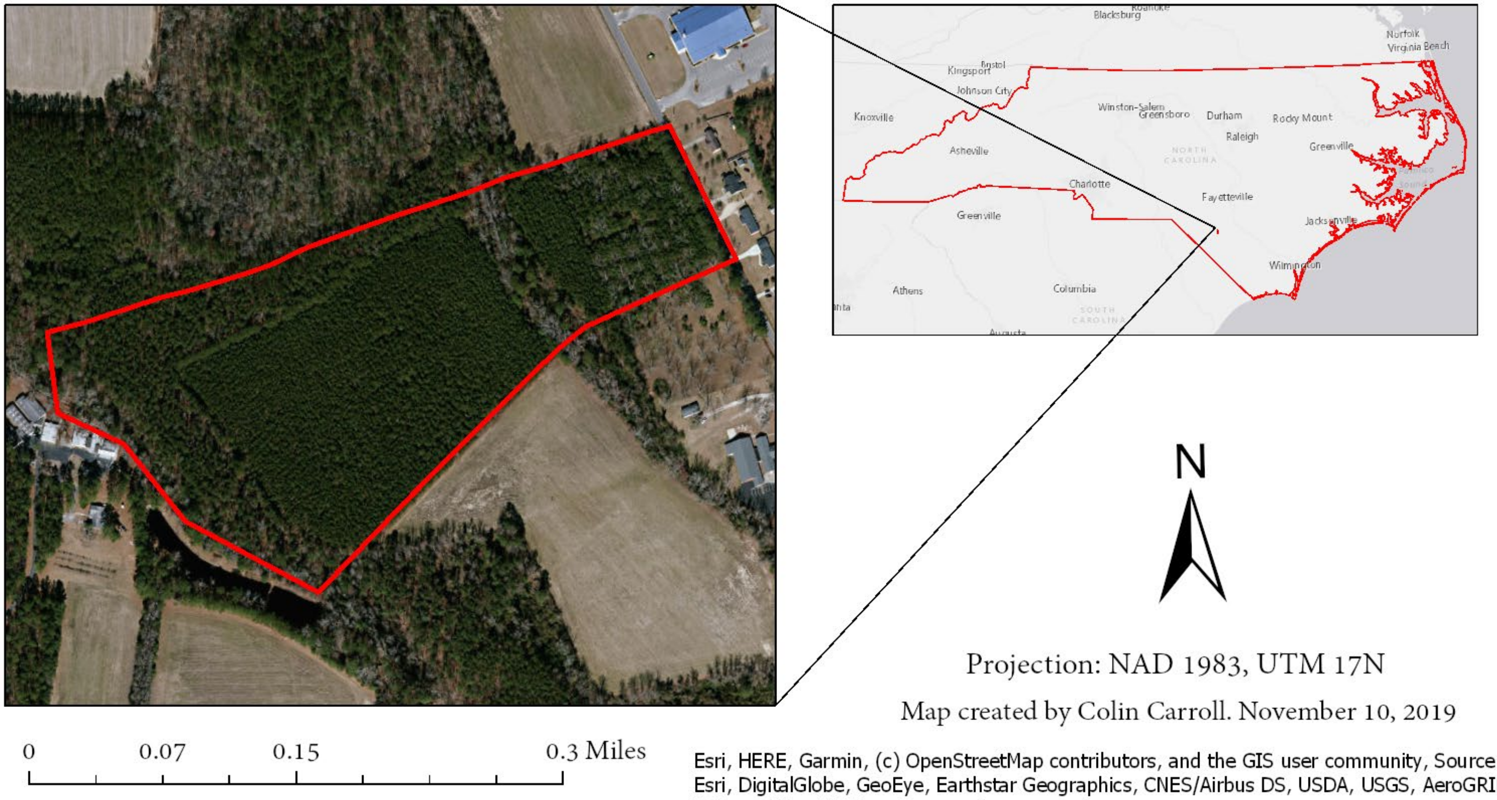
Appendices

Appendix A: Map of study site

Study Site: RH Stephens Tract near Lumberton, NC



Projection: NAD 1983, UTM 17N

Map created by Colin Carroll. November 10, 2019

Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Appendix B: Radiative transfer model

The path length of light (in the direction of the sun) traveling through a tree row canopy volume that is characterized by known height and width and is continuous in the third dimension (row length) for E-W orientation was calculated as:

$$\textit{Path length: if } \tan(\theta) * \left(\frac{x+w}{\cos(\gamma)}\right) \leq h, \textit{then } L = \frac{w}{\cos(\gamma)*\cos(\theta)}$$

$$\textit{if } \tan(\theta) * \left(\frac{x+w}{\cos(\gamma)}\right) > h, \textit{then } L = \frac{w}{\cos(\gamma)*\cos(\theta)} - \frac{\tan(\theta)*(x+w)}{\sin(\theta)*\cos(\gamma)}$$

where:

h = dominant tree height
θ = solar zenith angle at time t
w = tree row width
γ = solar azimuth angle at time t
x = distance from tree row
L = light path length through canopy

Appendix C: Planting densities of spatial arrangements.

Trees per Hectare	Trees per Acre	Similar scenario planting density
228	92	2 tree row, 30 m of forage (*minimum possible timber)
380	154	3 tree row, 24 m of forage
543	220	4 tree row, 19 m of forage
820	332	5 tree row, 12 m of forage (*maximum possible timber)

Appendix D: Financial analysis assumptions

Annual returns used for CAPM and beta coefficient calculations.

Timber			Cattle		S&P 500
Year	Annual Return		Annual Return		Annual Return
2018	1.13%		0.77%		-11.22%
2017	-4.70%		6.40%		17.32%
2016	-3.63%		-12.05%		15.39%
2015	0.52%		-12.30%		2.45%
2014	3.78%		16.96%		15.50%
2013	5.71%		5.39%		23.38%
2012	-2.78%		4.04%		8.67%
2011	-14.29%		12.80%		-2.22%
2010	3.96%		25.76%		17.11%
2009	-13.34%		4.88%		35.02%
2008	-16.11%		-7.07%		-34.48%

CAPM				10-year
Risk free rate	0.67%		Timber	2.01%
Market Rate (Rm)	9.80%		Cattle	2.67%