

**EFFECTS OF BLACK WALNUT AND HONEY LOCUST ON FORAGE
GROWTH, SOIL WATER, AND SOIL QUALITY INDICATORS**

by

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Effects of Black Walnut and Honey Locust on Forage Growth, Soil Water, and Soil Quality Indicators

Scott A. DeBruyne

Abstract

The goal of this research was to determine the interactions between forage and tree components of a silvopasture system. There were two studies performed on separate but adjacent sites established in 1995 at Virginia Tech's Kentland Research Farm located on a river terrace in the ridge and valley region of central Appalachia. The objective of the first study was to determine the influence of honey locust and black walnut silvopastures on physical, chemical and biological indicators of soil quality when compared to open pasture. The objective of the second was to determine if silvopasture systems changed forage mass production compared to open pastures, and how forage growth was linked to changes in soil water with increasing distance from the trees and beneath black walnut and honey locust trees compared to shade cloth.

The study on soil quality indicators was performed in a silvopasture that had previously been grazed by sheep and cattle. Trees had been planted on a 2.4 X 12.4 m spacing. Samples were collected from the upper 15 cm of soil at 1.6 m, 3.0 m, and 6.1 m from the tree rows, soil cores were collected from the top 10 cm of soil at the same spacing. Soil chemical, physical, and biological indicators were most favorable in the honey locust silvopastures and less favorable in open pastures and black walnut silvopastures. Total N ($p= 0.0219$) and extractable K ($p= 0.0347$) were significantly greater in honey locust silvopastures. Values for NH_4 , Ca, Mg, Mn, and B were numerically greater in the honey locust silvopastures. Biological and physical properties

were more favorable in honey locust silvopastures. The honey locust plots had the highest total C ($p= 0.0216$) and microbial organic C ($p= 0.0255$). In all treatments, the highest concentration of soil nutrients and best soil physical and chemical properties were observed 1.5 m from the tree stem.

Forage growth and soil water were measured in silvopastures in 2006 and 2007. Samples were collected at 1.0 m, 2.0 m, and 3.6 m from the trunk of the trees, or plot center, under honey locust, black walnut, and shade cloth in 2006 and 2007. Soil water was measured in the top 10 cm of soil using a capacitance type probe, and at 30 cm intervals from 45-105 cm using a neutron probe. Forage was harvested four times in 2006 and three times in 2007 to determine dry mass. In 2006 there was higher forage growth in the black walnut and honey locust than under 70% shade cloth. In 2007, with a 50% shade cloth, forage growth was similar in all treatments. Initial soil water content was highest under shade cloth in 2006, and in 2007 the rate of soil drying was lower under shade cloth compared to the rate of soil drying beneath the trees.

The trees did not negatively effect forage growth. Though there were differences in water use patterns in the surface soil beneath trees compared to shade cloth, the lack of a negative effect on forage growth indicates that the change is likely not biologically significant. Silvopasture systems improved the soil quality indicators compared to open pasture.

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I. Introduction

Introduction

Silvopasture is the integration and intensive management of trees, forage, and livestock into a single land unit (Clason and Sharrow, 2000). The concept behind silvopastures is that multiple species in an ecosystem can improve resource capture while creating advantageous interactions among the different plant and animal components (Jose et al., 2004). Species differ in their ability to acquire surrounding resources and in the timing and extent of their resource use. Pines, for instance, can utilize forms of phosphorous unavailable to grasses, and nitrogen fixed by legumes improves the growth of associated plants (Chen et al., 2002).

Silvopastures can be established by planting trees into a pasture, establishing forage beneath trees, or simultaneously planting both trees and forage. Silvopastures are different from forest grazing in terms of management and scale (Clason and Sharrow, 2000). Silvopastures are managed for the production of all components and management may include pruning of trees, liming and fertilization, weed control, and various forage management activities.

The basis for silvopasture is that the combination of trees, forage, and animals produces synergistic interactions that potentially improve the production of all three. Moderate shading, for instance, can increase forage growth in silvopastures and improve nitrogen use (Jose et al., 2004; Wilson and Wild, 1991). Other potential benefits of silvopastures include frost protection, weed control through allelopathy, increased pH, and improved soil fertility, the effects of these factors on forage growth, however, are of yet uncertain (Feldhake, 2002; Scott and Sullivan, 2007). Tree growth in silvopastures is

often greater than in plantations due primarily to the low planting densities and the greater availability of nutrients from fertilization and livestock feces (Clason and Sharrow, 2000). Improved animal performance in silvopastures has been attributed to tree shelter for improving animal comfort, but improved digestibility of forage crops and higher forage yields may also contribute (Buegler et al., 2006; Le Houérou, 2006).

The establishment and maintenance of silvopastures provides benefits to producers, the environment, and society at large. Financial benefits to producers provided by silvopastures include increased revenues from animals due to improved animal performance and lower feeding and fertilizer costs. Producers can also receive income from new sources such as timber, hunting leases, carbon credits, and non timber forest products such as fruits and nuts (Workman et al., 2003; Husak and Grado, 2002; Stainback and Alvalapati, 2004). Production diversification has the added benefit of increased income stability for the producer. Improved quality of life and aesthetics are also important, but frequently overlooked benefits (Etienne and Rapey, 1999).

The functional values of silvopastures also provide benefits to the environment and society. The deeper rooting of the trees provides a safety net that can catch nutrients that have leached beyond the rooting zone of the associated forage thereby protecting ground water from non point source pollution (Nair et al., 2007). Silvopastures provide improved habitat for a wide variety of birds, and have higher bird diversities than pastures (Schultz et al., 2000). More carbon is sequestered in silvopastures, and, if widely planted, silvopastures could have a substantial impact by sequestering up to 9 Tg C yr⁻¹ (Montagnini and Nair, 2004). Silvopastures improve land use by maintaining or

increasing food production while also providing a supply of high value timber and other crops (Workman et al., 2003).

There are several costs and issues associated with silvopasture systems not associated with pure pastures or plantations. Silvopasture establishment is more expensive and requires more technical expertise than plantations or pastures (Shrestha and Alavalapati, 2004). Subsequent maintenance of silvopastures is more intensive as the producer must protect the trees from competition from the forage and damage by livestock and other animals (Fike et al., 2004). Timing and management of harvests and other activities in silvopastures requires more planning to avoid equipment and labor shortages and potential conflicts between land uses (Workman et al., 2003).

The adoption of silvopastures in the southeastern US is increasing. Zinkhan and Mercer (1997) found that silvopastures are the most commonly adopted production focused agroforestry practice in the southern US due to increased economic returns and production diversification. Other authors have found very different reasons for adoption of agroforestry practices. In a survey of Alabama and Florida landowners, Workman and associates (2003²) found that landowners perceive aesthetics, shade, and environmental improvement as the greatest benefits of agroforestry, and the most frequently listed perceived problems were increased competition in agroforestry systems and a lack of knowledge. Similar views were found in France; Etienne and Rapey (1999) reported that landowners perceived aesthetics and quality of life issues as the primary benefits of agroforestry adoption, frequently overlooking potential economic benefits.

The agroforestry plots for our research were established in 1995 at the Virginia Tech's Kentland farm. The research site is located 10 km southwest of Blacksburg at 37°

11° N latitude and 80° 35' W longitude, in the Ridge and Valley province of Virginia at an elevation of 545 m. The dominant soils on the site are fine textured Ultisols and Alfisols formed on terraces of the New River. Rainfall is evenly distributed throughout the year averaging 1000 mm annually. Average January low and high temperatures are -6.7°C and 4.6°C, and the average low and high July temperatures are 15.0°C and 28.0°C, respectively, with 155 frost free growing days per year (Cregger and Hudson, 1985).

Objectives

The overall purpose of this research was to determine the effects of black walnut (*Juglans nigra* L.) and honey locust (*Gleditsia triacanthos* L.) on a temperate silvopasture. There were two studies, each investigating different aspects of the silvopasture system interactions. The goals of these studies were to determine the effect of the tree species on soils, forage growth, and soil water.

In the first study we evaluated the effects of black walnut and honey locust on soil quality indicators. Specific objectives were to: 1. determine if there were differences in soil quality indicators between the silvopastures and open pasture, and 2. determine how these differences changed with increasing distance from the tree row. The hypothesis was that the silvopastures would have more favorable indicators of soil quality than the open pasture and that the effect of the silvopasture would be largest near the tree row and decrease with increasing distance from the tree.

There were three objectives in the second study. Specific objectives were to: 1. determine effects of tree species on forage growth and how that changed with distance from the tree; 2. determine if there were differences in soil water among treatments or at increasing distances from the tree or plot center, and 3. evaluate whether the differences

in soil water were correlated with differences in forage growth. Our hypothesis was that hydraulically lifted water from trees to the forage would promote increased forage growth resulting in higher forage yields near the tree and lower forage yields with increasing distance.

II. Literature Review

Introduction

Forests are the climax ecosystems across most of the eastern United States, of which Appalachia is a part. Forests provide many goods and services, such as tight nutrient cycles, an increase in soil organic matter and soil carbon, maintenance of high levels of biodiversity, and a wide array of forest products. Large scale deforestation and conversion of land to agriculture has resulted in soil degradation and erosion and the soil fertility functional benefit of forests has been replaced by amending soils with lime and fertilizers.

Agroforestry introduces the benefits provided by forests to agricultural settings through the intentional integration of woody plants. Agroforestry practices have the potential to reduce environmental impacts of agriculture, improve the economic viability of agriculture, and increase total productivity of land while mitigating risks to producers. These benefits become more important with increased demands on land due to population growth. If global food production is to keep pace with growing populations and greater wealth, more marginal land will be cultivated and more meat will be produced; this must be done while improving water and nutrient use efficiency and maintaining and restoring soil fertility (Tilman et al., 2002).

Principles of Agroforestry

Agroforestry practices

Many different cropping and management practices are included in agroforestry. These practices mimic the form and functions of forest and savanna and other mixed species ecosystems to enhance the productivity and sustainability of agricultural systems.

Some practices use the intact forest directly, such as the use of forested riparian buffers to protect the water quality in streams and rivers, or forest farming of shitake mushrooms and ginseng (Olson et al., 2000). Other practices include swidden agriculture, and managed woody fallow agricultural systems which rely on the re-growth of forests to enrich the soil (Young, 1997¹; Ashton, 2000).

Other systems incorporate trees into traditional agricultural systems. Alley cropping, silvopasture, and parks incorporate trees at varying densities into cropping and pasture systems (Olson et al., 2000). These systems normally use the trees to increase the production of the cropping system but can also be used to accomplish environmentally based goals such as planting on the contours of slopes to prevent soil erosion (Young, 1997³). The use of windbreaks is commonly practiced in the United States; this practice protects the soil from wind erosion while also reducing transpiration and increasing crop growth (Brandle and Hodges, 2000). The use of woody fallows is common in many parts of the world. Woody fallows are similar to swidden systems, but tend to use a much shorter rotation period and will often use a single leguminous woody species to raise soil fertility (Young, 1997¹).

Several practices sometimes included in agroforestry include the use of green manures, and harvested fodder. The lack of direct interactions between trees and crops has meant that some disagree with classifying such practices in agroforestry (Olson et al., 2000).

Crop production

Interactions between the different components of agroforestry can result in an increase in total on farm productivity. The production of any single component in an

agroforestry system may be decreased, but the combination of components in an agroforestry system produces a higher total output though improved resource capture on the site (Ashton, 2000). Wanvestraut et al. (2004) observed this in a pecan alley crop in Florida where cotton lint yields were lower in the cotton alley crop than in the mono-cropped cotton, but the added value from the pecan nuts would likely have compensated for a lower cotton crop (Ares and Brauer, 2006). Similar interactions can be seen in pine based agroforestry systems which have been widely implemented in the southeastern United States. When competition due to shading is controlled through proper tree spacing and management forage growth is rarely negatively effected. Total productivity from the system is increased by supplying timber, and potentially pine straw, as well as forage (Clason and Sharrow, 2000).

There are also advantages from agroforestry systems when timber and nuts are the goal for the producer rather than more traditional agricultural goods. The benefit to trees of such a system was observed by Chiffot and associates (2006) who found that hybrid walnuts (*Juglans nigra* L. X *Juglans regia* L.) and wild cherry trees (*Prunus avium* L.) had higher growth rates in alley-crops than when grown alone at the same density. The authors suspect that the increase was due to higher nitrogen availability from fertilizer added to the intercropped grains. Production of fodder and crops early in the rotation provides added income from otherwise un-cropped land, reducing financial risks to the farmer.

Synergistic interactions between crops and trees can help boost the relative productivity and provide the benefits of improved resource capture. This phenomenon has been discussed by Young (2000¹) in tropical woody fallow systems where farmers

were able to sufficiently increase crop yield to make up for the fallow period while also gaining the wood as a fuel source. In Chiapas, Mexico, Soto-Pinto et al. (2000) found that coffee produced higher yields under 23-38% shade than did trees in full sun, and the shading trees provided a variety of goods to the farmers. Throughout the world windbreaks or shelterbelts are employed to increase crop productivity by protecting soil resources, decreasing transpiration, increasing water input and providing potential timber and woody crops for landowners (Bradle and Hodges, 2000). Forest gardens provide a particularly extreme example of increased productivity, as the combination of up to several dozen species in complex multi-strata systems are able to produce far more than any single crop could (Cuanalo de la Cerda and Guerra Mukul, 2008).

Silvopastures improve livestock performance, increase forage yield, reduce requirements for soil amendments, and produce marketable forest products such as timber and nuts (Husak and Grado, 2002; Ares et al., 2006). The interactions between trees and grasses in silvopastures and savanna systems have been widely studied, but the contributing interactions are still poorly understood. Jose and collaborators (2004) report that though many crop species tend to have reduced yield when shaded, yields of pasture species tend not to change or may even increase under moderate shading. In Virginia, Buegler and associates (2005) found a 20% increase in cool-season forage production under moderate tree cover and no change in forage production under heavy and light tree cover. Forage production was greater under black walnut than honey locust. In West Virginia, Belesky (2005) observed the highest leaf mass in orchard grass under partial canopies with 40-70% shade when compared to orchard grass that was open grown or growing under a full canopy with 90% shade. In north-eastern Australia, Durr and

Rangel (2002) observed 90% greater forage production under leguminous rain trees (*Samanea saman*) than in adjacent open areas.

However, reduced forage growth was observed when light is the limiting resource, in richer soils, and in cooler climates (Wilson, 1998). Burner (2003) found that orchard grass growth was greater in a loblolly pine silvopasture than in an open pasture, while tall fescue and a fescue/orchard grass mix performed best in the pasture and worse in silvopastures. McGraw and collaborators (2005) found that alfalfa growth was reduced by 44% under black walnut in Missouri. In Boonsville, Arkansas, Burner and Belesky (2008) found that tall fescue produced less than one third the biomass under severe shade (11-17% of full) in a loblolly pine silvopasture than did open grown fescue when both were irrigated.

Forage growth is often only part of the equation in silvopastures because certain tree species produce mast or browse which can be consumed by animals. In Arkansas, Burner et al. (2005) found that pollarded black locust had enough leaf mass of sufficient nutrient quality for it to be used as fodder for cattle during the summer when grasses enter semi-dormancy and forage production decreases. Similar results in northern Greece by Ainali and Tsiouvaras (1998) showed that black locust provided a suitable feed source for livestock during the summer and winter and that it did not compete with associated forage when maintained as a low shrub. Le Houérou (2006) suggests that planting trees and shrubs in degraded and arid lands increases the ability of producers to feed livestock and protect soil properties.

Though the interactions between trees and forages are unclear, the research on animal performance in silvopastures has been largely positive. Kallenbach and associates

(2006) measured a 20% reduction in forage production in a hybrid pine-walnut silvopasture in Missouri, but animal performance was the same in the two systems. These findings may be due to increased animal comfort provided by the trees. Nutritional content of forage could also be contributing. Studies by Buerger et al. (2006) and Norton et al. (1990) found higher crude protein content in grass grown under shade. Planting shrubs also reduces wind speeds and water use by both animal and forages (Le Houérou, 2006)

Economics

Implementation of agroforestry practices can enhance the economic viability of farm land for producers by increasing total farm productivity, diversifying income sources, and reducing farm inputs. The ability of silvopasture, and other agroforestry practices, to produce multiple products creates a hedge that insulates producers against fluctuations in the market and poor growing conditions for any one crop (Nair et al., 2004). This is particularly important because the volatility of crop prices can create boom and bust cycles for producers. Agroforestry moderates income because the farmers derive revenues from a range of sources including livestock, timber, pine straw, and hunting leases which respond to different market forces.

The tree component of agroforestry is essential to the economic viability of the system. In the southeast, much research has been done on the potential to grow nut producing and high value timber species such as pecan and black walnut in agroforestry settings. The Missouri Department of conservation (2008) reported that black walnut stumpage prices in Missouri averaged \$1072 per m³ (\$2530 per MBF) for veneer and \$305 per m³ (\$720 per MBF) for sawtimber in 2007. Black walnut sawlog prices can

vary widely base on log quality and local market prices, while black walnut veneer logs have a national market which stabilizes the value somewhat (Hatcher et al., 1998).

Timber value can be an issue when producers are also trying to harvest nut crops off of their black walnuts because improved nut yielding varieties suffer from defects that reduce log quality (Ares and Brauer 2004). Black walnuts have a national market with a price that averages \$0.15 per Kg (Hatcher et al., 1998). Year to year variability in nut production can be an issue with black walnut: Improved tree varieties have higher and more consistent nut yields than native stock and because nut prices are inversely related to nut availability producer income was relatively stable (Ares and Brauer 2004).

The integration of fast growing, low value, tree species into agroforestry systems provide producers a source of income from wood grown for fuel and pulp. In Uttar Pradesh India, Jain and Singh (2000) found that incorporating poplar plantations into farms increased farmer income while providing fuel wood sources for the community and a pulp wood supply to a local paper mill. The integration of fast growing hybrid poplar into agricultural fields as a bio-fuel crop has been widely researched and could provide farmers in developed countries with an additional source of income (Ruark, 2006)

Silvopasture is used by livestock producers to increase forage production and farm profits. Garret and associates (2004) report that financial analyses show that silvopasture systems in the southern US consistently improve financial performance compared to pure plantations or pure pasture systems. Clason (1999) found that loblolly pine silvopastures compared favorably to loblolly pine plantations when the right forages were used; two of three forage types in silvopastures had a higher future net value than the pine plantation. Husak and Grado (2002) found that silvopastures performed

favorably against pastures, pine plantations, corn, soybeans and rice, especially when hunting leases are incorporated. In Mississippi, Grado et al. (2001) found that the internal rate of return of a silvopasture compared favorably to some pastures systems and suspect that improved timber values realized by pruning and using improved genetic stock would improve the relative performance of silvopastures. Longleaf pine silvopastures had a higher land expectation value than either pine plantations or open pastures because of the timber value and pine straw production, and their performance was further improved when carbon sequestration credits were included (Stainback and Alvalapati 2004). Lowered management costs are another benefit of silvopastures because the trees reduce the fertilizer and liming requirements by improving nutrient cycling and reducing leaching. This has become particularly important recently because costs of P and N increased by 80% and 100%, respectively, from 2000 to 2007 (USDA, 2007).

Environmental sustainability

Several agroforestry practices are used primarily to protect natural resources. Shelterbelts and riparian forest buffers are two of the most prominent practices of this sort. The use of shelter belts to reduce wind speed has been widely adopted around the world to increase crop yields, prevent loss of soil, and lower transpiration and evaporation on crop lands (Brandle and Hodges, 2000). Forested riparian buffers can protect streams and rivers by filtering runoff, protecting stream ecosystems, and providing habitat for numerous species (Machtans et al., 1995; Gregory, 1991). From a water quality stand-point, a 30 m riparian buffer can filter out over 90% of sediments and N, 80% of P from runoff water while also protecting the stream from thermal pollution

though shading of the stream and increased runoff infiltration (Schultz et al., 2000). The contributions of riparian buffers to water quality are particularly important because agricultural impacts are the largest source of impairment for rivers and streams (EPA, 2007).

Agroforestry also shows promise in reducing groundwater pollution caused by agriculture. Research in Florida by Nair et al. (2007) shows that the use of alley cropping practices could reduce the leaching of nutrients into local ground water systems. Ground water benefits are also provided tangentially because the tighter nutrient cycling in agroforestry systems means fewer applications of fertilizer are required for pasture maintenance, which improves water quality and reduces non-point source pollution (Mekonnen, 1997; Nair et al., 2007; McDowell et al., 2001; Young, 1997(2)).

Agroforestry practices can combat land degradation. Le Houérou (2006) suggests that establishing trees and shrubs in semi-arid and degraded landscapes around the world provides a myriad of advantages including reducing erosion, improving soil fertility, and providing fodder and shelter to livestock. Planting trees on the contour of slopes reduces erosion and improves water infiltration on hillsides allowing for continued agricultural use of the land (Young, 1997³). In Madrid Spain, Alegre et al (2004) found that leguminous shrubs were better able to improve degraded soils than sclerophyllous species native to the region. Lefroy and Stirzaker (1999) proposed the use of silvopastures to prevent salinization of soils in Australia by using trees to prevent the water table from rising. The potential of maintaining tree cover for long term soil resource protection was shown by Daniels et al. (1983) who observed leaching of clays from surface to deeper soils many years following the conversion of forests to pasture systems.

Habitat modification and diversification through agroforestry practices produce valuable side effects. The inclusion of trees into agricultural land increases diversity on a landscape level and has been shown to locally raise the species diversity of birds (Schultz et al., 2000). The establishment of longleaf pine silvopastures in the southeast could aid in the recovery of the endangered red cockaded woodpecker (Stainback and Alvalapati, 2004). Establishment of forested riparian buffers increases plant diversity, provides habitat for a wide variety of birds and protects streams and rivers from agricultural runoff (Machtans et al., 1995; Gregory, 1991; Schultz et al., 2000).

Tree/crop/soil Interactions

Resource utilization

Interactions between trees and forages can lead to improved resource use. Levesley and associates (2004) found higher soil water storage under maize monocultures than in senna-maize, or gevillea-maize alley cropping systems. Using stable isotopes in a study in a savanna in Arizona, Weltzin and McPherson (1997) found that most of the water up-take by Emory oaks over two years old was from deeper soil horizons not accessed by associated bunchgrass. Lefroy and Stirzaker (1999) concluded that the inclusion of ally cropping systems into the grain producing areas of southern Australia could prevent increased salinity in land under cultivation by increasing water utilization. In Argentina, Fernadez and associates (2008) observed partitioning of soil water usage between ponderosa pine and mixed grasses where 75-90% of the water used by grasses came from the upper 20 cm and less than 20% of the pine's water came from the same layer. In northern Kenya, Lehmann and associates (1998) found complementary interactions between sorghum and *Acacia saligna* where crop roots

dominated the surface soil between tree rows and trees accessed deep soil water, allowing for more complete utilization of water resources. In a review of the subject, Ong and Swallow (2003) note that higher total yields from agroforestry systems in semi-arid regions are often linked to higher water use as trees use water deep within the soil during the dry season when crops can't be grown (also a form of improved temporal resource use). They also note that trees can improve water infiltration by creating natural terraces and reducing transpiration requirements through shading and reduction in wind speeds.

Trees' deeper rooting allows them to keep nutrients cycling in the plant-soil system for longer periods of time by absorbing nitrogen and nutrient cations that have leached beyond the rooting zones of the forage species (Thevathasan and Gordon, 1997; Nair et al., 2007; Gindaba, 2005). In the Sahel and in western Kenya, Ong and Leakey (1999) report that deep rooted plants were able to absorb nitrogen that had moved beyond the reach of the shallow rooting crop species. In an experiment in a sandy loam soil in western Florida, Allen and associates (2004) observed 64% reduction of N leached from a pecan-cotton alley cropping system in which the trees were allowed to root freely, compared to plots in which root barriers were installed.

Trees are also able to utilize otherwise unavailable forms of P, though studies have generally not shown an increase in P availability for forage growth (Chen et al., 2002; Buresh and Tian, 1998). In a pot study by Scott and Condon (2004), radiata pine P uptake was higher than P uptake by lucerne or perennial ryegrass pots when total P levels were low. The pine was also better able to utilize and mineralize organic P. On New Zealand's south island, Chen and associates (2000) observed decreased concentrations of organic P, and increases in inorganic P following the establishment of a

radiata pine plantation in grassland indicating increased use of organic P by the radiata pine.

In West Virginia, Belesky (2005) observed the highest leaf mass in orchard grass under partial canopies with 40-70% shade compared to orchard grass that was open grown or growing under a full canopy with 90% shade. In Virginia, Buergler and associates (2005) found a 20% increase in cool-season forage production under moderate tree cover and no change in forage production under heavy and light tree cover. In northern Australia Wilson and Wild (1991) measured greater growth in tropical grasses under shade when nitrogen was the limiting factor for growth. Similar increases in growth were not observed when the grasses were grown under the same light and nutrient levels in a pots study, indicating that there was a change in soil processes or soil plant interactions.

Temporal interactions between trees and crops are another important consideration in resource sharing and competition between trees and plants. The potential for complementary interactions are best seen in *Faidherbia albida* which has been described as having a “reverse phenology” because it leafs out during the dry season and drops its leaves at the beginning of the rainy season (Roupsard et al., 1999). *F. albida* makes use of light and deep water resources during the dry season when other crops cannot be grown, is capable of biological nitrogen fixation and provides forage for livestock which make it an important multipurpose tree in sub-Saharan Africa (Baumer, 1992; Buresh and Tain, 1998). Examples of temporal resource partitioning are seen in black walnut and honey locust which leaf out late in the spring and drop their leaves early in the fall. This limits competition between the trees and pasture grasses for light and

water during spring and fall. During the mid summer when the growth of most cool season grasses slows down, black walnut and honey locust provide shade which can help maintain forage growth (Ball et al., 2002).

Hydraulic lift

Hydraulic lifting of water is the passive movement of water from areas of high water potential to areas of low water potential through the root systems of plants. The redistribution of water to surface soil by trees through hydraulic lift provides a potential means of reducing drought stress to companion crops in silvopastoral systems (Caldwell et al., 1997).

Even though it's relatively small, the amount of water translocated by hydraulic redistribution should not be dismissed. Since trees may have root systems that reach several meters below ground, they can potentially access a much larger volume of water than can most grasses and other shallow rooted plants. The importance of hydraulic lift to the water status of trees was shown in research in Oregon by Brooks and associates (2002) who observed nightly rewetting of soil under ponderosa pine averaging 21% and 29% of their daily water use at 20-60cm and 60-100 cm, respectively. Emerman and Dawson (1998) reported similar findings in New England where they measured sugar maple (*Acer saccharum*) hydraulically lifting 102 L of water per night, and stable isotope measurements indicated that the trees may be moving much more. This process occurs in reverse as well. In Utah, Leffler et al. (2005) found that senesced plants helped rewet deep soils through passive movement of water from wetter surface soils to dry deeper soils through what the authors describe as "reverse hydraulic lift." It has also been

suggested that hydraulic redistribution might play an important role in desert plants by allowing the growth of shallow rooted shrubs around deep rooted trees (Zou et al., 2005).

The extent to which hydraulic redistribution of water affects forage growth and productivity is still uncertain. In Utah, Leffer and associates (2005) found that senesced cheatgrass increased the rate of rewetting in subsurface soil horizons compared to plots cleared of vegetation. Corak and associates (1987) found that a corn (*Zea mays*) plant was able to survive when it's only source of water was water transferred by the root system of an alfalfa (*Medicago sativa*) plant under simulated drought conditions, the presence of hydraulic lift was then confirmed by watering the alfalfa with deuterium then measuring the corn for elevated deuterium levels. Throughout the study, there were no measurable changes in soil water due to hydraulic lift. In north-east Spain Peñuelas and Filella (2003) supplied a root of a *Pinus nigra* tree with deuterium labeled water and found that surrounding plants had increased foliar deuterium concentrations indicating hydraulic lift by the pine and water parasitism of surrounding plants. In a Texas savanna Zou and associates (2005) found that the removal of trees increased water stress on shallow rooting plants but not deep rooting plants. The degree to which hydraulic lift improves crop growth is uncertain, Ludwig and collaborators (2004) found that under *Acacia* trees in east Africa soil water and forage growth increased after root trenching, showing that any potential benefits of hydraulic redistribution were negated by increased water usage by the trees.

Nutrient cycling

Fertilization is a major and growing cost associated with the management of pastures (USDA, 2007). With their deeper rooting, trees absorb nutrients that have

leached beyond the rooting zones of the forage species and returned some of these nutrients through root turn-over and leaf fall (Thevathasan and Gordon, 2004; Gimdaba et al., 2005). Trees can also utilize nutrient resources not available to most crop species and leguminous tree species increase soil N as well as providing numerous other benefits.

Nutrients that otherwise leach from a site are captured by trees and returned to the soil surface through the trees' litter fall and root turnover. Higher levels of soil nutrients have been observed under mature trees in the savannas of Africa, Central and South America and North America, though the nutrient transfer to some extent may be from surrounding surface soils and animal inputs rather than the capture of leached nutrients (Ong and Leakey, 1999). In a study of two different soils in north-eastern Queensland, Australia, Jackson and Ash (2001) found that the soil concentrations of C, total N, and K were significantly higher under the tree canopies than in the soils beyond the canopies of single narrow-leaf ironbark eucalyptus (*Eucalyptus xanthoclada* and *E. drepanophylla*). Elderidge and Wong (2005) measured declines in Ca, K, Mg, and pH with increasing distance from isolated boxwood trees (*Eucalyptus melliodora*), though there were no differences in C, N, or S concentrations; however, C, N, and S declined after tree death. Higher total soil nutrient contents were associated with increased mineralization rates of nitrogen and other nutrients as has been found under *Colophospermum mopane* (Gindaba, 2005, Thevathasan and Gordon 1997). In a savanna in Zimbabwe, Mlambo and associates (2007) measured a greater than doubling of N accumulation, N mineralization, and microbial carbon under large trees than in the intercanopy areas. In a forest soil study in the Cumberland Plateau of eastern Kentucky, Washburn and Arthur (2003) found significantly higher Ca in the O horizon and upper mineral soil in forest plots with

red maple understories than in portions of the forests without red maple. They attributed the difference to greater acquisition and turnover of Ca by the red maple.

Nutrient cycling is enhanced by the larger amount of soil organic matter found within agroforestry systems, which can help buffer pH and raise CEC. Dahlgren and associates (1997) found an increase in soil pH in the A and AB horizons of soils under oak canopies in an oak savanna in California. In northwestern Connecticut Dijkstra and Smits (2002) observed higher total and exchangeable Ca in the surface soil under sugar maple compared to northern hemlock. Because the sugar maples had many more fine roots deeper in the soil profile than did the hemlocks, they concluded that the increase in Ca was due to translocation of Ca from subsurface to surface soil horizons.

Soil amelioration

Research has been done to see if these benefits can be achieved in an agricultural setting as a means of reducing agricultural inputs and improving the productivity of marginal lands. Thevathasan and Gordon (2004) found that poplar trees in a southern Ontario alley cropping experiment were able to increase soil organic carbon by 1% and increase soil N content over the course of eight years. In an oak savanna in California, Dahlgren and associates (1997) measured increased soil carbon in all soil horizons. Montagnini and Nair (2004) estimated that adopting agroforestry practices in suitable areas of the US would sequester 90 Tg C yr^{-1} of C, with alley cropping sequestering $73.8 \text{ Tg C yr}^{-1}$, silvopastures sequestering 9 Tg C yr^{-1} per year, and various other agroforestry practices sequestering the rest. Higher soil organic carbon is also a contributing factor to lower bulk density under trees as has been observed by Tate and associates (2004),

Dahlgren et al (1997), and Young (1997). As previously mentioned, integration of trees into degraded lands can also increase soil nutrient content and site productivity.

Microclimate modification

The addition of trees to agricultural landscapes modifies the light, temperature, wind speed, rainfall and other climatic characteristics of the land. Depending on the interactions between these factors, the effect of trees on crops can be either positive or negative. The positive aspects are best seen in windbreaks where the trees can reduce wind speed and increase snow accumulation to a distance of twenty times the height of the trees (Brandle and Hodges, 2000). The trees in silvopasture provide positive climatic effects to the livestock by lowering temperatures during the summer and reducing wind speeds (Clason and Sharrow, 2000). The microclimate effects of trees on forage are mixed. Shading has been found to increase forage yield for some species and decrease it for others, and the shading effects of the tree vary depending on species characteristics and relative position of the tree to the forage, or other crop (Wilson, 1996; Belesky, 2005; Cruz, 1997; Kohli and Saini, 2003). In a study in West Virginia, Feldhake (2002) found orchardgrass, growing under 77% cover in a mixed pine silvopasture, was less prone to suffer damage during radiant frost events because the temperature was up to 10.4°C warmer than open pastures on nights with a risk of radiant frost.

Allelopathy

Many species of trees and plants produce allelopathic compounds that can inhibit the growth of other plants. In agroforestry there is concern that the value of black walnut and pecans for their wood and nuts may be negated because of their release of juglone, an allelopathic chemical. Juglone production is not necessarily bad; it will hamper or kill

many plant species, but others are allowed to grow with reduced competition (Scott and Sullivan, 2007; Ercisli, 2005). In a study by Wanvesterat and associates (2004) in Florida, cotton lint yield in a pecan-cotton alley crop with root barriers was higher than the lint yield in plots without root barriers, but no different than yield in cotton monocultures plots. In greenhouse and field experiments in Missouri, Houx and associates (2008) found that the application of old walnut husks increased the growth of orchardgrass and red clover compared to control plots, but they speculate that the juglone in the husks may have been oxidized prior to application.

Within silvopasture systems the allelopathic effects of tall fescue on trees is much more pronounced than tree effects on fescue. The tall fescue understory suppressed walnut growth and reduced dominant height from 11 m to 6.3 m (Ares and Brauer, 2004). Smith and associates (2002) found that the growth of newly established pecan trees was higher when herbicides were used to clear a 1.83 m radius or larger circle of tall fescue forage from around the base of the trees than when less forage control was implemented. Celette, et al. (2005) discovered that grapes grown with tall fescue yielded 30% less fruit than grapes grown without a ground cover. The authors suggest that decreased growth in grapes was due to nutrient competition or allelopathy from the fescue. In a field study in central Missouri, Alley et al. (1999) reported that tall fescue significantly reduced the growth of honey locust and black walnut seedlings, but not pitch loblolly hybrids.

Appalachians Land Use and Farming

The Appalachian region of the United States has 32.3 million acres of pasture and cropland (26.1% of Appalachian region) and 71.5 million acres of forest (58%) (USDA, 2002). Farms in the Appalachian region of the United States averaged 152 acres in size

in 1997 which was well below the national average of 487 acres (USDA, 1999). Crop yields in the region were lower than national averages and livestock was responsible for much of the farm income in Appalachian states (Colyer, 2001).

The predominance of small farm size and the large amounts of hilly and marginal lands in the Appalachian region make silvopasture a viable and potentially important agricultural practice. Adoption of silvopasture might be helped by its growing popularity and potential for economic return. Zinkhan and Mercer (1997) found that silvopastures are the most commonly adopted production-focused agroforestry practice in the southern US due to increased economic returns and production diversification. Farmers may also choose to adopt agroforestry practices for other reasons. In France, Etienne and Rapey (1999) found that farmers sought agroforestry practices as a way of improving the farm environment while enhancing their quality of life; timber revenues were often overlooked.

Research Gaps

Most of the research into agroforestry practices has been conducted in tropical regions of the world. The temperate regions of the world have been largely ignored and very few of the available crops and trees have been studied to determine their viability within agroforestry systems. Further research should be conducted to understand the interactions between the different components of agroforestry systems to produce information that can be used by farmers to better implement agroforestry practices. Such research will also uncover unexpected problems and issues facing agroforestry practices. In a pine silvopasture establishment study in east Texas Oswald et al. (2008) found that loblolly seedlings had a higher survival rate than longleaf pine; This was not due to

climatic factors or resource availability, but because wild hogs buried many long leaf pine seedlings while grubbing in the sprayed rows and the loblolly pine seedlings were tall enough not to be buried.

Agricultural productivity more than doubled between 1948 and 1996, with reduced labor and increased mechanization and agrochemical inputs (Padgitt et al., 2000). The next doubling of food production will need to incorporate more tools than the last for this growth to be sustainable. Agroforestry practices have the potential to more efficiently utilize land that will be brought into production to help feed a growing world.

III. Influences of Black Walnut (*Juglans nigra* L.) and Honey Locust (*Gleditsia triacanthos* L.) on Soil Quality Indicators in a Mid-Atlantic Appalachian Silvopasture

Abstract

Until the last three decades, little research on the benefits of silvopastures has been done in temperate regions of the world. As a result, the effects of temperate agroforestry systems on soil quality are not well understood. The objective of this research was to determine the influence of honey locust (*Gleditsia triacanthos* L.) and black walnut (*Juglans nigra* L.) silvopastures on physical, chemical and biological indicators of soil quality compared to open pasture. The study was conducted in 11 year-old-honey locust and black walnut silvopastures in central Appalachia. Soil samples for chemical and biological analysis were collected from the upper 15 cm of soil, and soil cores for physical analyses were collected from the top 10 cm of soil in all treatments at 1.6 m, 3.0 m, and 6.1 m from the tree rows.

Soil chemical, physical, and biological indicators were most favorable in the honey locust plots and were less favorable in open pastures and black walnut silvopastures. Total N and extractable K were significantly higher in honey locust silvopastures than in black walnut or open pastures. NH₄, Ca, P, Mg, Mn and B were also higher in soils under honey locust though the differences were not statistically significant. Biological and soil physical properties were more favorable in honey locust silvopastures; they had the highest total C and microbial organic C and the lowest bulk density. The highest concentration of soil nutrients and the best soil physical and chemical properties were observed beneath the tree canopy, and lower values were in the

row centers in all treatments. Silvopasture systems improve the soils through increased organic matter input and nutrient accumulation. Similarities in spatial patterns of soil quality indicators in the open pasture and silvopastures are likely due to nutrient deposition and capture by trees from within the open pasture plots. The establishment and long term maintenance of silvopastures in the southern Appalachians could reduce the need for soil amelioration by livestock producers.

Introduction

Forests are the climax ecosystems across most of the eastern United States within which Appalachia is located. Forests provide many goods and services such as tight nutrient cycles, sustaining high levels of biodiversity, providing a wide array of forest products, and sequestering soil organic matter and soil carbon. Large scale deforestation and conversion of land to agriculture resulted in soil degradation and erosion, and the soil fertility functional benefit of forests has been replaced by amending soils with lime and fertilizers. Silvopasture, the intentional introduction of trees into pastures, is an agricultural system that attempts to reintroduce many of the benefits of forests into livestock production systems to improve the environmental sustainability of the system while increasing farm profits.

Silvopastures have been shown to increase income for livestock producers (Garret et al., 2004; Clason, 1999). Silvopastures reduce requirements for soil amendments, improve livestock performance, increase forage yield, and produce marketable forest products such as timber and nuts (Husak and Grado, 2002; Ares et al., 2006). Fertilization is a growing cost for producers; P and N fertilizer prices increased by 80% and 100%, respectively, between 2000 and 2007 (USDA, 2007; Cole, 2008).

Establishing trees into pastures decreases the loss of existing nutrients due to leaching and runoff thereby decreasing the amount of fertilizer and lime needed to maintain productivity particularly when leguminous trees are used (Mekonnen et al., 1997; Nair et al., 2007; Young, 1997). Reducing fertilizer application rates improves the producers' profitability by lowering costs while improving water quality by reducing non-point source pollution.

Trees' deep rooting allows them to keep nutrients cycling in the plant-soil system for longer periods of time by absorbing nitrogen and nutrient cations that have leached beyond the rooting zones of associated forage species (Thevathasan and Gordon, 1997; Nair et al., 2007; Gindaba, 2005). In the Sahel and in western Kenya, Ong and Leakey (1999) reported that deep rooted plants were able to absorb nitrogen that had moved beyond the reach of the shallow rooting crop species. In an experiment in a sandy loam soil in western Florida, Allen and associates (2004) observed 64% reduction of N leached from a pecan-cotton alley cropping system in which the trees were allowed to root freely, compared to plots in which root barriers were installed.

Nutrients that are otherwise leached from a site are captured by trees and returned to the soil surface through the trees' litter fall and root turnover. Higher levels of soil nutrients have been observed under mature trees in the savannas of Africa, Central and South America and North America, though the nutrient transfer to some extent may be from surrounding surface soils and animal inputs rather than the capture of leached nutrients (Ong and Leakey, 1999). In a study of two different soils in north-eastern Queensland, Australia, Jackson and Ash (2001) found that the soil concentrations of C, total N, and K were significantly higher under the tree canopies than in the soils beyond

the canopies of single narrow-leaf ironbark eucalyptus (*Eucalyptus xanthoclada* and *E. drepanophylla*). Elderidge and Wong (2005) measured declines in Ca, K, Mg, and pH with increasing distance from isolated boxwood trees (*Eucalyptus melliodora*), though there were no differences in C, N, or S concentrations; however, C, N, and S declined after tree death. Higher total soil nutrient contents were associated with increased mineralization rates of nitrogen and other nutrients under *Colophospermum mopane* (Gindaba, 2005; Thevathasan and Gordon, 1997). In a savanna in Zimbabwe, Mlambo and associates (2007) measured a greater than doubling of N accumulation, N mineralization, and microbial carbon under the canopy of large mopane (*Colophospermum mopane*), a leguminous tree, compared to intercanopy areas. A forest soil study in the Cumberland Plateau of eastern Kentucky by Washburn and Arthur (2003) found significantly higher Ca in the O horizon and upper mineral soil in forest plots with red maple understories, than in portions of the forests without red maple. They attributed the difference to greater acquisition and turnover of Ca by the red maple.

Trees are also able to utilize otherwise unavailable forms of P, though studies have generally not shown an increase in P availability for forage growth through increased P mineralization (Chen et al., 2002; Buresh and Tian, 1998). In a pot study by Scott and Condrón (2004), radiata pine P uptake was greater than P uptake by lucerne (*Medicago sativa*) or perennial ryegrass (*Colium pereune*) when total P levels were low. The pine was also better able to utilize and mineralize organic P. On New Zealand's South Island, Chen and associates (2000) observed decreased concentrations of organic P, and increased inorganic P following the establishment of a radiata pine plantation in

grassland. The authors attributed this to increased P mineralization and use of organic P by the radiata pine.

Incorporating trees into agricultural systems can increase soil C. Thevathasan and Gordon (2004) found that poplar trees in a southern Ontario alley cropping experiment had greater soil nitrification rates and were able to increase soil organic C by 1% over the course of eight years. In an oak savanna in California, Dahlgren et al. (1997) measured increased soil carbon in all soil horizons beneath 80 to 100 year old blue oaks (*Quercus douglasii*) and interior live oaks (*Q. wislizenii*) compared to open grasslands. Montagnini and Nair (2004) estimated that adopting agroforestry practices in suitable areas of the US would sequester 90 Tg C yr⁻¹ of C, with alley cropping sequestering 73.8 Tg C yr⁻¹, silvopastures sequestering 9 Tg C yr⁻¹, and various other agroforestry practices sequestering the rest.

Research on silvopastures and other agroforestry practices in sub-Saharan Africa has shown that incorporating trees into agricultural systems can improve soil physical properties, increase available N, and maintain soil chemical properties such as pH and cation exchange capacity (Buresh and Tian, 1998). Dahlgren and associates (1997) found an increase in soil pH in the A and AB horizons of soils under oak canopies in an oak savanna in California. In northwestern Connecticut Dijkstra and Smits (2002) observed higher total and exchangeable Ca in the surface soil under sugar maple compared to northern hemlock. Because the sugar maples had many more fine roots deeper in the soil profile than did the hemlocks, they concluded that the increase in Ca was due to Ca translocation from subsurface to surface soil horizons. Young (1997) stated that the ability of trees to raise soil pH in silvopasture systems may not be great enough to replace

liming, but the tree effects can ameliorate the acidifying effects of fertilizer application and can reduce the adverse effects of low pH by decreasing the potential of aluminum toxicity.

Soil biology is also influenced by trees. In an alley cropping study in Florida, Lee and Jose (2003) found higher soil respiration and fine root biomass in a cotton alley crop than in a pasture or open cotton field; however, microbial biomass was the same in the alley crop and pasture, and the open cotton field had the least microbial biomass. In a savanna in Zimbabwe, Mlambo and associates (2007) found higher levels of microbial biomass in the soils under large trees than under either small trees or intercanopy areas.

Interactions between tree and pasture species have a range of potential effects on silvopasture soils. Black walnut (*Juglans nigra* L.) produces juglone, an allelopathic compound that could be detrimental to the soil microbial community. However, negative effects on the microbial community have yet to be observed in field studies (Thevathasan et al., 2005). Differences in rooting patterns are also likely to be significant due to the tendency of black walnuts to produce taproots while honey locust (*Gleditsia triacanthos* L.) has a more spreading root system (Akinnifesi et al., 1999). Combining trees and forages can also result in segregation of rooting. In Argentina, Fernandez and associates (2008) observed partitioning of soil water usage between ponderosa pine and mixed grasses, where 75 to 90% of the water used by grasses came from the upper 20 cm and less than 20% of the pine's water came from the same layer.

Until the last three decades, little research on the benefits of silvopastures has been done in temperate regions of the world. The overall purpose of our research was to determine the effects of black walnut and honey locust on soil quality in a temperate

silvopasture. The specific objective of this study was to evaluate the spatial effect of the silvopasture system on soil quality indicators including soil nutrients, bulk density, porosity, microbial activity, microbial carbon and total soil carbon.

Methodology

Study area

The research site is located 10 km southwest of Blacksburg at 37° 11' N latitude and 80° 35' W longitude, in the Ridge and Valley province of Virginia at an elevation of 545 m. Soils are classified as fine textured, mixed, mesic, Typic Hapludults, with slopes ranging from 10-25%, and fine-loamy, mixed, mesic, Fluvaquetic Eutrudepts in the stream bottoms (Cregger and Hudson, 1985). Rainfall is evenly distributed throughout the year averaging 1000 mm annually. Average January low and high temperatures are -6.7°C and 4.6°C and the average low and high July temperatures are 15.0°C and 28.0°C, respectively, with 155 frost free growing days per year (Cregger and Hudson, 1985). Management activities that occurred on the research site prior to and during this study are summarized in Table III.1.

This study was conducted on Virginia Tech's Kentland Research Farm. Silvopasture plots were planted in 1995 with honey locust (HL), black walnut (BW) and open pasture (OP). The study area was nine, 0.3-ha plots with three blocks of the three treatments in a randomized block design (Figure III.1). Within each of the silvopasture treatments, the trees were planted at a 2.4 X 12.2 m (8 X 40 ft) spacing. The honey locust had an average height of 6.9 m and diameter of 7.9 cm and the black walnut had an average height of 5.6 m and diameter of 8.6 cm.

Soil samples were collected between October 2006 and January 2007. Samples for chemical and biological analyses were collected from the top 15 cm of soil, and soil core samples for analysis of physical properties were collected to a depth of 5 cm. Sampling was performed systematically in a grid type arrangement (Figure III.2). The grid was composed of five transects running perpendicular to the tree rows. Samples were collected at 1.5, 3, and 6.1m from each tree row along the five transects (Figure III.2). Samples were composited by distance from the tree row (e.g. all soils at the 1.5m points in transect A were combined). Soil core samples and fresh soil samples for biological analysis were collected in the same manner, but they were only collected from transects A, C, and E (Figure III.2). Sampling of the OP plots occurred in the same manner as on tree plots except that distances were based off the plot boundaries rather than distance from the tree rows.

Physical properties

Bulk density, porosity, and water holding capacity of the soils were measured using the intact soil cores. Soil porosity and water holding capacity were measured using a tension table (Dane and Hopmans, 2002). Bulk density was measured by drying the cores to constant weight at 105°C and dividing the soil weight by its volume as described by Danielson and Sutherland (1986).

Soil nutrients and fertility

Soil samples were sieved and air dried prior to testing for micro and macro nutrient content, pH, CEC, base saturation, and total C. Inorganic N was measured using a 1.0 M KCl extract and then determining NO_3^- and NH_4^+ spectrophotometrically (Traacs 200 analytical consol, Bran & Luebbe, Germany). Total N and C were determined using

a CNS analyzer (VarioMax CNS, Elementar, Germany). Plant available K, P, Ca, Mn, Mg, Cu, Fe, Zn and B were extracted with the Mehlich I extract (Sims, 1996) and analyzed using inductively coupled plasma spectrometry (ICP) at the Virginia Tech Soils Testing Lab. Soil pH was measured in a 1:1 soil to water suspension (Thomas, 1996). Soil CEC was estimated using extractable Ca, K, and Mg from the Mehlich I extract and the extractable acidity estimated using the Mehlich buffer pH (Sims, 1996).

Biological properties

Fresh soil samples were collected in January, 2008, and measured for biological indicators of soil quality. Chloroform fumigation was used to estimate microbial biomass. All samples were fumigated for 42 hours, extracted using 80 ml of K₂S₀₄ solution and passed through a Whatman #2 filter paper (Jenkinson and Powlson, 1976). Vials of extract solution were refrigerated until they could be measured for organic C concentration by high temperature oxidation using a liquiTOC II (Elementar, Germany) analytical console.

Soil microbial activity was estimated based on soil concentrations of ATP. Fresh soil samples were collected in January of 2008 and analyzed within 48 hours of collection. Soil samples were kept refrigerated (4°C) when they were not being processed. Prior to extraction, samples were sieved through a 2-mm sieve to remove coarse material. Soil (10 ± 0.20 g) was placed into a centrifuge tube with 50 ml of 0.137-M NaCl. The centrifuge tubes were then shaken for 10 minutes, allowed to settle for 20 minutes, then spun in a centrifuge for 10 minutes at 2000 rpm. Samples of the solution were collected from each centrifuge tube and prepared using a luminescence assay kit

(ATPlite™, Perkins Elmer, USA) and analyzed on a luminescence counter (Topcount NXT Liquid Scintillation Counter, Perkins Elmer, USA).

Data analysis

The data were checked for homogeneity of variance using Levene's test and normality was diagnosed visually using quantile-quantile plots (Levene, 1960). Where those conditions were not met, the data were transformed as appropriate. The data were analyzed as a split plot within a randomized block design, with pasture treatments as main plots and distance from tree as subplots. The analysis of variance (ANOVA) was conducted using a statistics analytical package (SAS 9.1.3 Service Pack 3). Least square means were used to determine significance among mean values following the ANOVA (Montgomery, 1984).

Results and Discussion

Physical properties

Silvopasture treatments had little effect, if any, on soil bulk density and porosity. Bulk density changed with distance from the tree, but there was no interaction between treatment and distance from the tree row (Tables III.2 and III.3). Though differences were not significant, there was a trend of silvopasture plots having lower soil bulk density and greater non-capillary porosity (Figure III.3A). Soil bulk density in silvopastures was highest outside the influence of the trees (6.1 m) and decreased with increasing tree influence (1.5 m) (Figure III.3B). Average bulk density between tree rows (6.1 m) was 1.30 g/cm^3 , the same as the bulk density of the OP. Nearest the tree rows (1.5 m) soil bulk density was 1.26 g/cm^3 , the same as the overall effect of HL and only slightly lower than the overall effect of BW (1.27 g/cm^3) (Table III.3). Lower bulk density under trees

has been observed by Tate and associates (2004), Dahlgren et al (1997), and Young (1997) under similar circumstances and is generally attributed to higher soil organic matter content. Based on our soil C values, (Table III.3) soil organic matter was significantly higher under HL ($p= 0.02$) than BW or OP.

Soil biological properties

Microbial C and organic C were all significantly affected by pasture treatment (Table III.2). Trends were similar to treatment effects observed in the soil chemical properties, with HL having the highest values, the OP having the lowest, and BW intermediate between the two (Figure III.3A). These differences may be due to the increased organic matter input by trees. Buresh and Tian (1998) reported that greater soil microbial C and larger soil invertebrates populations and were correlated with higher soil organic matter in the savannas and agroforestry systems of Kenya and Nigeria. Akinnifesi et al (1999) reported more surface roots in non-taproot-forming trees compared to taproot-forming trees in a study of the rooting habits of 13 multipurpose trees conducted in Ibadan, Nigeria. Since BW trees forms a taproot and HL does not, the potential differences in surface rooting could account for changes in total and microbial C. Higher organic matter content could also account for treatment differences seen in bulk density and porosity (Gorham, 1953; Jeffery, 1970; Federer et al., 1993), which were more favorable in the silvopastures than in the OP. Increased microbial C under trees has been observed by Mlambo et al (2007) in a mopane (*Colophospermum mopane*) savanna, and Lee and Jose (2003) observed higher microbial C in a 47 year old pecan-cotton alley cropping system compared to the open cotton field. Distance differences were notably absent except for soil C concentrations ($p= 0.105$) with increases from plot

center (6.1 m) toward the tree row. Soil ATP did not differ for any factor, likely due to very high variation in the measurements.

Soil fertility

Soil fertility indicators, pH, cation exchange capacity (CEC), base saturation (BS), Mg saturation (MgSat), Ca saturation (CaSat), and K saturation (KSat) were similar among all treatments (Tables III.4 and III.5). Distance effects on fertility indicators matched the pattern seen in soil nutrient contents; higher fertility levels occurred near the tree rows and decreased with distance from the tree (Figure III.4B). Even with the liming and fertilization, with time, the trends that were observed could become significant especially for the HL plots. Only K saturation had a distance X treatment interaction (Table III.3 and Figure III.5).

The lack of differences between treatments goes against observations in other studies where trees had positive effects on soil characteristics (Rao et al., 1998; Buresh and Tian, 1998), and likely reflects differences such as minimal, or lack of, fertilizer and lime inputs in those studies. One possible explanation is that the time available was sufficient for trees to begin concentrating nutrients beneath their canopies, but not long enough for these changes to become statistically significant.

Soil nutrient content

Total N and extractable K were affected by pasture treatments, and extractable Ca, Mg, Mn, and B were affected by distance from the tree row (Table III.6). Total soil N and K were highest in the HL plots (Table III.7). Concentrations of most of the cations were numerically greater in HL, lowest in OP and intermediate in BW (Figure III.6A). P concentrations in HL plots were similar to both BW and OP plots, but OP plots had

higher P concentrations than BW (Table III.7). The gradient of P concentration away from the stem of the tree was greatest in the HL plots (Table III.6 and Figure III.7). The increase of N and K could be due to higher organic matter and enhanced nutrient extraction and cycling by the trees' root systems (Gindaba et al., 2005; Buresh and Tian 1998). Differences between the silvopastures may be associated with differences in nutrient cycling and soil exploitation by roots. In addition to differences in root morphology, there may also be differences in fine root turnover and leaf litter decomposition rates (Fisher and Binkley, 2000; Montagnini et al., 2000).

Higher Ca, Mg, Mn and B contents were seen at the 1.5 and 3.0 m distances than at the 6.1 m row center (Table III.7 and Figure III.6B). There was a gradient of increasing nutrient content from row center (6.1 m) toward the tree. Except for K, the pasture and distance effects were independent of each other. (Table III.6). OP plots were adjacent to silvopasture plots and root barriers were not installed; edge effects might have created the variability seen in the OP plots and may account for the gradient of soil nutrients with distance observed in all treatments. It's likely that roots from trees in the HL and BW plots have spread extensively though the site and have accumulated nutrients from within the OP plots. In a review of the literature, Rao et al. (1998) mentioned that root competition from several species reduced corn growth at distances of up to 7 m from the tree rows. Investigating the rooting habits of the trees on this site to determine the extent of their spread into the adjacent plots should be a sufficient test for this hypothesis. The same gradient in nutrient content, with highest levels of soil nutrients under the tree has been observed under narrow-leaf ironbark eucalyptus (*Eucalyptus xanthoclada* and *E. drepanophylla*), poplar (*Populus* spp.), Sudan teak (*Cordia Africana*) and broad-leaved

croton (*Croton macrostachyus*) (Jackson and Ash, 2001; Thevathasan and Gordon 1997; Gindaba et al., 2005). Increased leaf deposition, higher concentrations and turnover of fine roots beneath the tree, and the scavenging of nutrients from surrounding areas have been proposed as reasons for this gradient (Buresh and Tian 1998, Thevathasan and Gordon 1997).

Conclusion

In the 11 years since the silvopastures were established their soil properties have deviated from those of the pastures. Soil quality has improved on the HL silvopasture sites which had significantly more N, C, K, and microbial C than the pasture as well as trend of greater numerical values for NH₄, Ca, Mg, Mn, B, CEC, non-capillary porosity and lower bulk density. Within treatments, soil nutrients were consistently highest under the trees and lowest at the row center. The same pattern appeared in the OP plots as well as silvopasture plots possibly due to a border effect from the trees adjacent to the OP plots. This study shows that trees in silvopastures improve soil quality and may reduce the need for fertilization.

Table III.1. Management activities that took place on the pasture treatments from 2003 to the time of this study.

Year	Season	Activities
2003	Spring	Overseeded with clover (2kg ha ⁻¹) and orchard grass(23 kg ha ⁻¹)
	Summer	Grazed by sheep
2004	Fall	Fertilized with 60 kg/ha N as urea, 40 kg ha ⁻¹ P as super-concentrated phosphate, and 50 kg ha ⁻¹ K as KCl
	Summer	Grazed by sheep
2005		Over seeded with 10 kg/ha "Kentucky 31" tall fescue
	Fall	Block 2 sprayed with Gramoxone Xtra (sprayed in bands at rate of 1.5 L ha ⁻¹) then drill seeded with "Kentucky 31" tall fescue (10 kg ha ⁻¹)
2006	Spring	Cinnamon red clover (5 kg ha ⁻¹) and Ladino Clover (2 kg ha ⁻¹)
	Summer	Grazed by cattle

Table III.2. Analysis of variance and source table for soil biological and physical quality indicators for pasture treatments.

	DF	Bulk Density	Non-capillary Porosity	Microbial ATP Index	Microbial Organic Carbon	Soil Carbon
Block	2	0.095*	0.7771	0.1902	0.0433**	0.03**
Pasture Treatment	2	0.4947	0.462	0.4622	0.0255**	0.0216**
Distance from Tree	2	0.003***	0.3458	0.383	0.7285	0.1051
Treatment*Distance	4	0.2847	0.678	0.701	0.121	0.9696

* Significant at $P < 0.1$, ** Significant at $P < 0.05$, *** Significance at $P < 0.01$

Table III.3. Mean values and standard deviations for soil biological and physical quality indicators as influenced by pasture treatment and distance from the tree.

		Bulk Density (g/cm ³)	Non-capillary Porosity (%)	Microbial ATP Index (count/ g)	Microbial Organic C (mg/kg)	Soil C (%)
Pasture treatment	Open Pasture	1.30 ± 0.07	17.5 ± 2.1	4654 ± 166.3	149.1 ± 16.8 b	2.044 ± 0.163 b
	Honey Locust	1.26 ± 0.03	20.9 ± 2.9	5205 ± 1100	215.6 ± 19.5 a	2.383 ± 0.068 a
	Black Walnut	1.27 ± 0.02	20.9 ± 1.0	4284 ± 421.2	183.7 ± 29.1 b	2.127 ± 0.121 b
Distance from tree	1.5 m	1.26 ± 0.04 b	20.3 ± 1.3	4737 ± 310	177.3 ± 22.5	2.228 ± 0.119
	3.0 m	1.27 ± 0.04 b	20.5 ± 1.3	4487 ± 412	189.7 ± 39.7	2.193 ± 0.112
	6.1 m	1.30 ± 0.04 a	19.2 ± 1.0	4920 ± 822	181.3 ± 1.9	2.147 ± 0.105

† Means sharing a letter do not differ $P < 0.05$

Table III.4. Analysis of variance and source table for indicators of soil fertility as influenced by pasture treatment and distance from the tree.

	DF	CEC	Base Saturation	Ca Saturation	Mg Saturation	K Saturation	pH
Block	2	0.0568*	0.5686	0.0846*	0.495	0.3495	0.8276
Pasture treatment	2	0.36	0.8331	0.2365	0.5102	0.2317	0.9989
Distance from tree	2	0.2039	0.0294**	0.0296**	0.1968	0.415	0.0681*
Treatment*Distance	4	0.6659	0.6294	0.1076	0.9411	0.0757*	0.3281

* Significant at $P < 0.1$, ** Significant at $P < 0.05$, *** Significance at $P < 0.01$

Table III.5. Mean values and standard deviations for indicators of soil fertility.

		Cation Exchange Capacity (%)	Base Saturation (%) [†]	Ca Saturation (%) [†]
Pasture treatment	Open Pasture	6.6 ± 0.6	96.5 ± 1.0	59.3 ± 0.8
	Honey Locust	7.2 ± 0.2	97.7 ± 1.6	59.9 ± 1.3
	Black Walnut	6.9 ± 0.6	95.4 ± 1.1	58.3 ± 0.8
Distance from tree	1.5 m	7.1 ± 0.5	97.4 ± 0.2 a	59.7 ± 0.4 a
	3.0 m	6.9 ± 0.4	96.2 ± 0.6 b	58.8 ± 0.6 b
	6.1 m	6.8 ± 0.5	96.0 ± 1.1 b	59.1 ± 0.9 ba

		Mg Saturation (%)	K Saturation (%)	pH [†]
Pasture treatment	Open Pasture	31.4 ± 0.7	5.8 ± 0.1	6.55 ± 0.114
	Honey Locust	32.3 ± 0.8	5.5 ± 0.5	6.67 ± 0.105
	Black Walnut	31.9 ± 0.2	5.2 ± 0.2	6.61 ± 0.105
Distance from tree	1.5 m	32.3 ± 0.5	5.4 ± 0.2	6.67 ± 0.014 a
	3.0 m	31.9 ± 0.5	5.6 ± 0.2	6.59 ± 0.009 b
	6.1 m	31.4 ± 0.6	5.5 ± 0.3	6.59 ± 0.045 b

[†] Means sharing a letter do not differ $P < 0.05$

Table III.6. Analysis of variance and source table for soil nutrient content for pasture treatments .

	DF	N	NH ₄	NO ₃	P	K	Ca	Mg	Zn	Mn	Fe	B
Block	2	0.0286**	0.5482	0.3227	0.0129**	0.041**	0.4384	0.6754	0.028	0.0411**	0.1271	0.9391
Pasture treatment	2	0.0219**	0.2506	0.4314	0.0631*	0.0347**	0.2425	0.2389	0.4232	0.9769	0.1313	0.3701
Distance from tree	2	0.2036	0.4171	0.2479	0.0124**	0.1556	0.0159**	0.0294**	0.0125**	0.0745*	0.2659	0.0118**
Treat.*Dist.	4	0.7372	0.4846	0.2224	0.0114**	0.1971	0.2186	0.7688	0.5747	0.2526	0.2751	0.5278

*Significant at $P < 0.1$, ** Significant at $P < 0.05$, *** Significance at $P < 0.01$

Table III.7. Mean values and standard deviations for soil nutrient content as influenced by pasture treatment and distance from the tree.

	N (%) †	NH ₄ (mg/g)	NO ₃ (mg/g)	P (mg/kg)	K (mg/kg) †	Ca (mg/kg) †
Pasture treatment						
Open Pasture	0.181 ± 0.013 b	0.0058 ± 0.0004	0.009 ± 0.0008	14.6 ± 1.1 b	124 ± 10.3 ba	661 ± 50
Honey Locust	0.211 ± 0.007 a	0.0076 ± 0.0003	0.008 ± 0.0006	14.9 ± 2.8 ba	135 ± 6.9 a	767 ± 47
Black Walnut	0.187 ± 0.013 b	0.0063 ± 0.0012	0.008 ± 0.0013	12.9 ± 0.7 a	116 ± 3.3 b	689 ± 44
Distance from tree						
1.5 m	0.196 ± 0.010	0.0065 ± 0.0004	0.0087 ± 0.0007	14.6 ± 1.3 a	127 ± 4.0	732 ± 9 a
3.0 m	0.195 ± 0.011	0.0071 ± 0.0003	0.0086 ± 0.0008	14.5 ± 1.9 a	127 ± 8.0	698 ± 26 b
6.1 m	0.191 ± 0.009	0.0062 ± 0.0009	0.0075 ± 0.001	13.3 ± 0.4 b	122 ± 8.2	690 ± 36 b

	Mg (mg/kg) †	Zn (mg/kg) †	Mn (mg/kg) †	Fe (mg/kg) †	B (mg/kg) †
Pasture treatment					
Open Pasture	212 ± 15	1.2 ± 0.4	19.4 ± 6.6	5.9 ± 0.7	0.38 ± 0.03
Honey Locust	250 ± 14	1.2 ± 0.1	19.7 ± 2.2	5.1 ± 0.4	0.45 ± 0.05
Black Walnut	227 ± 15	1.1 ± 0.1	19.1 ± 4.3	4.9 ± 0.3	0.41 ± 0.06
Distance from tree					
1.5 m	240 ± 9 a	1.2 ± 0.1 a	20.1 ± 4.4 a	5.1 ± 0.3 b	0.43 ± 0.03 a
3.0 m	229 ± 4 ba	1.2 ± 0.1 a	19.6 ± 4.3 ba	5.3 ± 0.4 ba	0.41 ± 0.04 b
6.1 m	222 ± 11 b	1.1 ± 0.2 b	18.7 ± 3.8 b	5.5 ± 0.5 a	0.40 ± 0.04 b

† Means sharing a letter do not differ $P < 0.05$

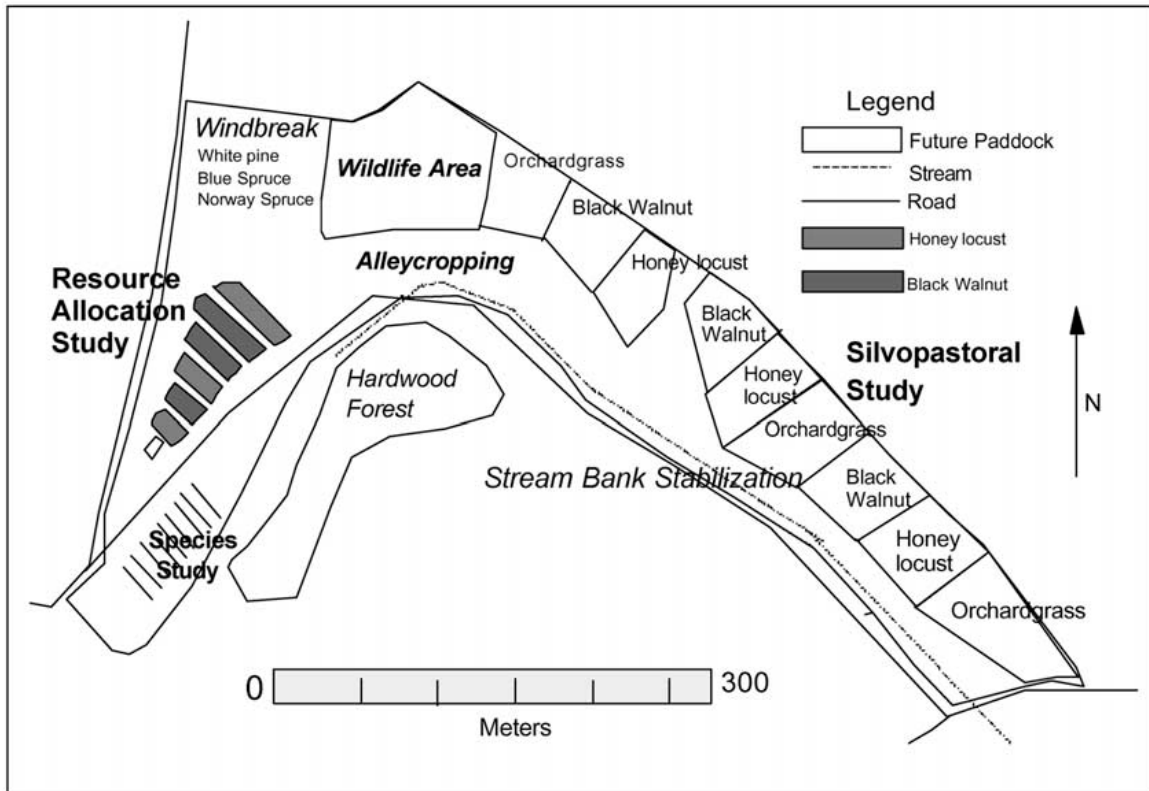


Figure III.1. Kentland farm agroforestry research and demonstration project area.

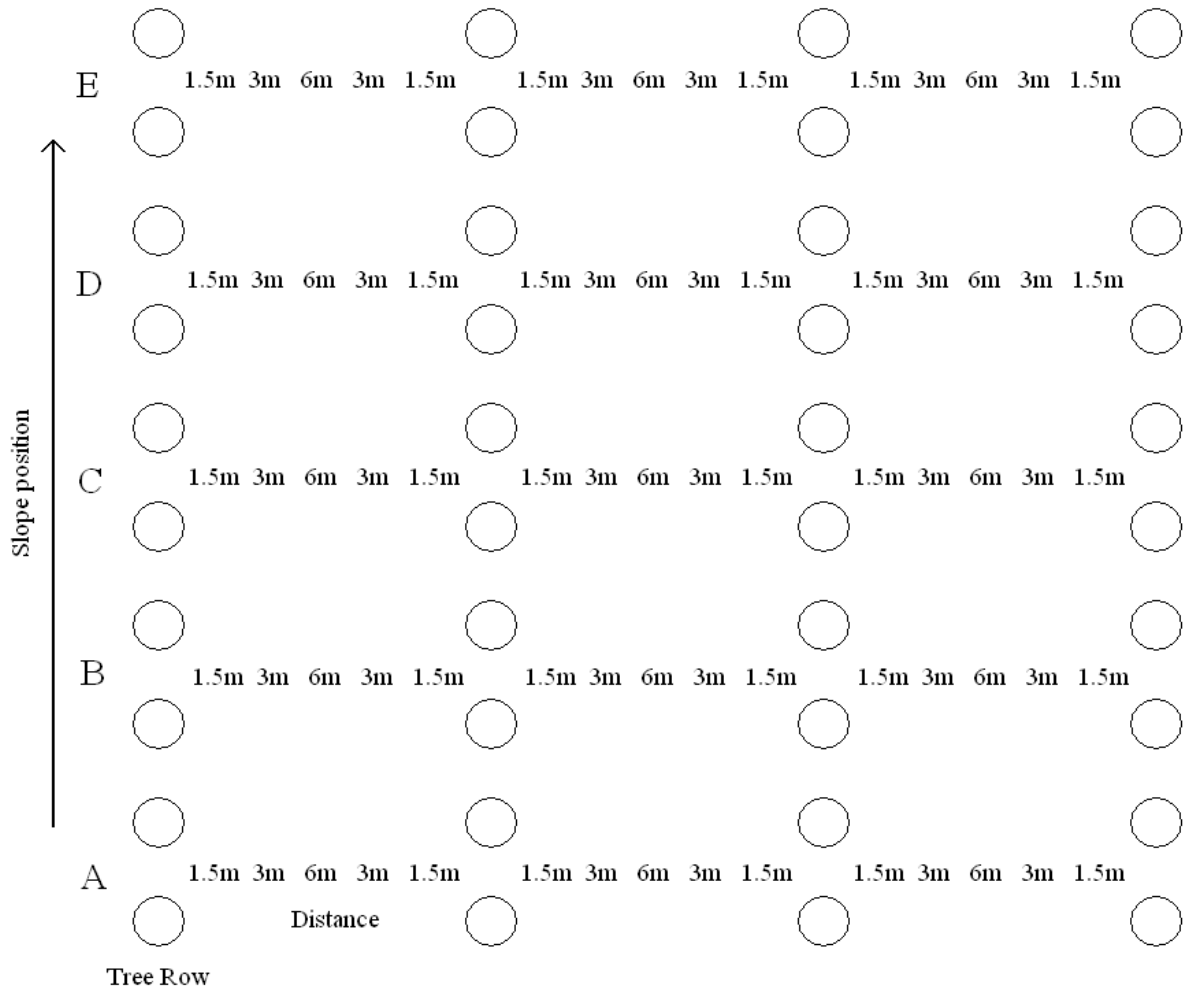


Figure III.2. The idealized sampling layout for the silvopasture soil quality indicator study, slope positions are denoted as A-E, with A at the bottom of the slope and E at the top. Sampling points are denoted by their distance from the tree row. Samples between Different tree rows within a treatment were composited during collection.

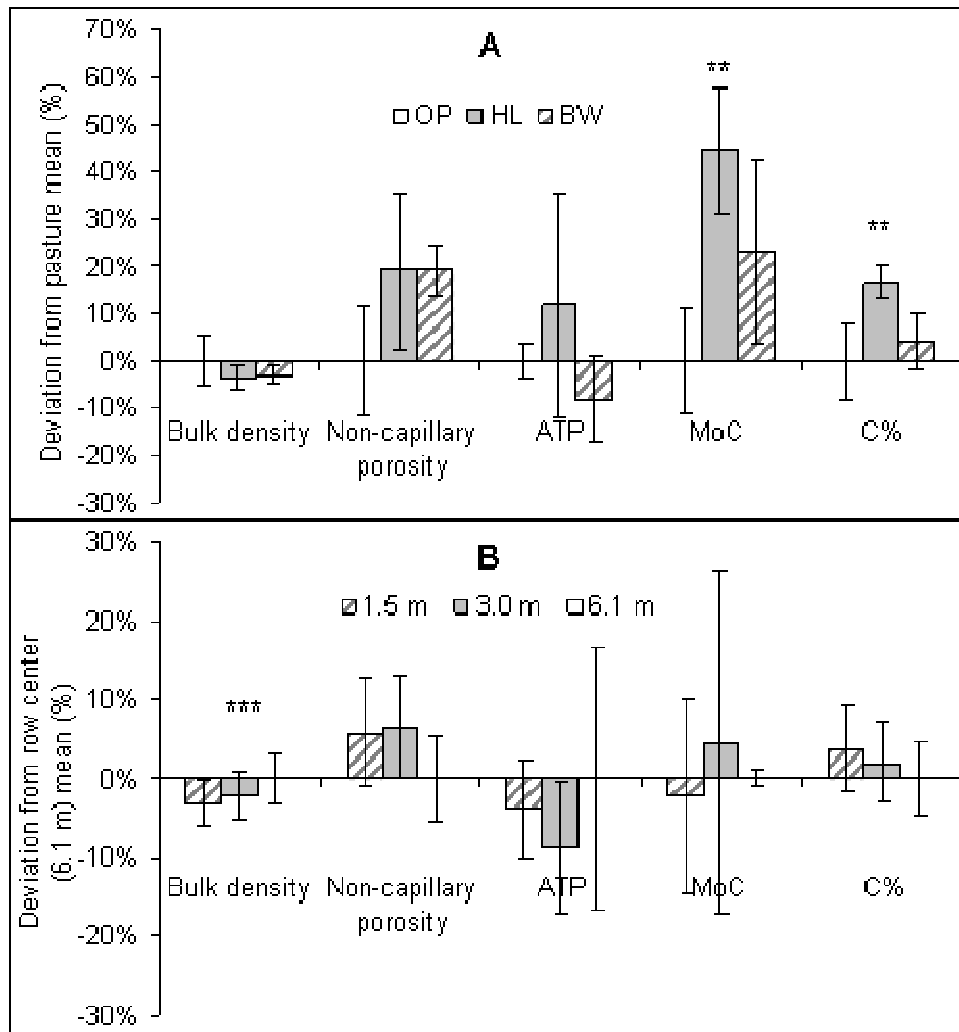


Figure III.3. Graphic representation of the relative values of soil physical quality and biological indicators in honey locust (HL) and black walnut (BW) silvopastures relative to that of the open pasture (OP) (A). Soil physical quality and biological indicators at 1.5 m and 3.0 m relative to the values at row center (6.1 m) (B).

* Significant at $P < 0.1$, ** Significant at $P < 0.05$, *** Significance at $P < 0.01$

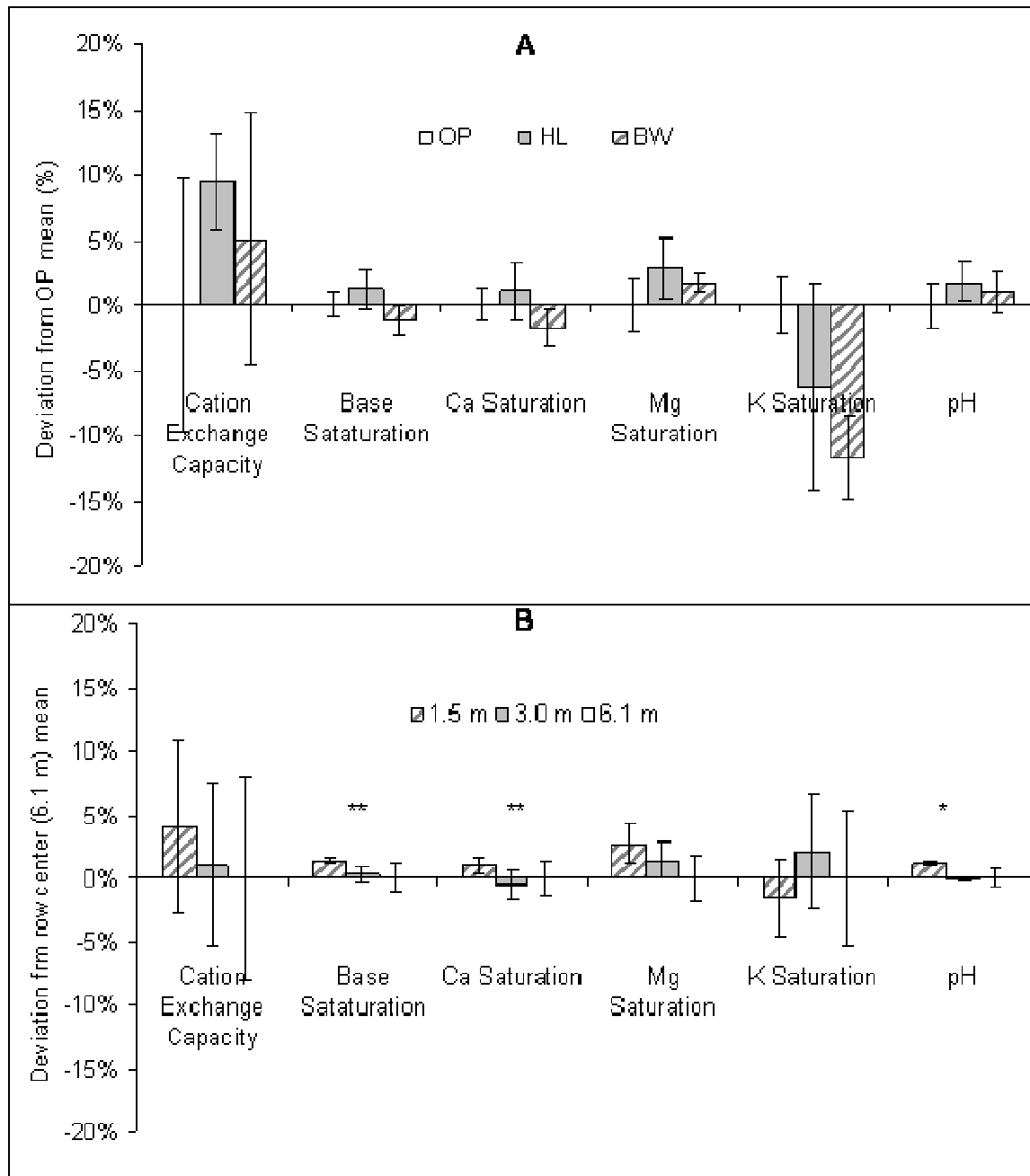


Figure III.4. Graphic representation of the relative values of soil fertility indicators in honey locust (HL) and black walnut (BW) silvopastures relative to that of the open pasture (OP) (A). Indicators of soil fertility at 1.5 m and 3.0 m relative to the values at row center (6.1 m) (B).

* Significant at $P < 0.1$, ** Significant at $P < 0.05$, *** Significance at $P < 0.01$

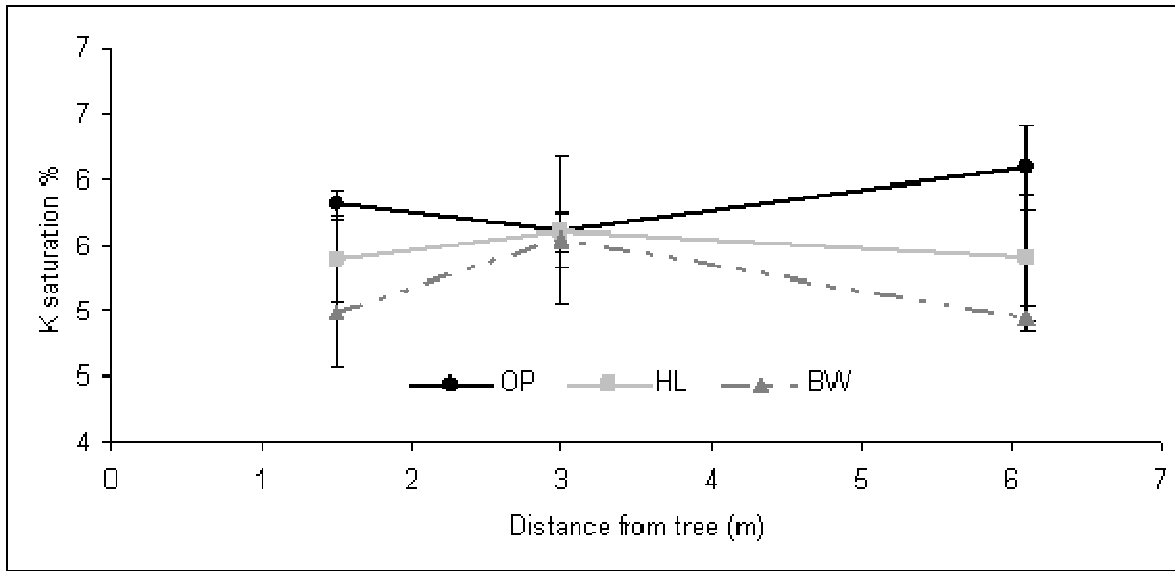


Figure III.5. K saturation values by treatment and distance, bars equal one standard deviation from the mean.

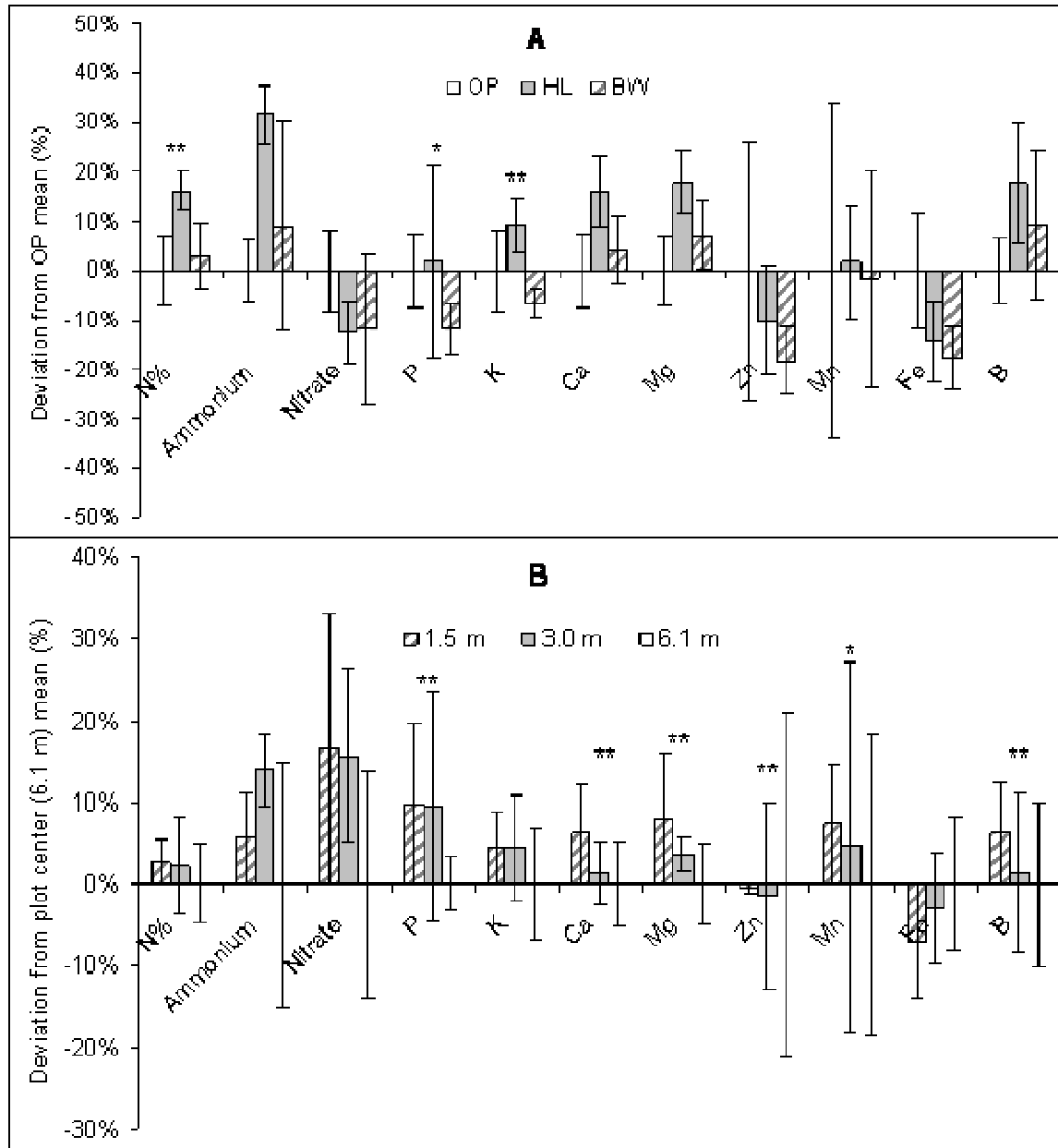


Figure III.6. Graphic representation of the relative concentrations of soil nutrient content in honey locust (HL) and black walnut (BW) silvopastures relative to that of the open pasture (OP) (A). Soil nutrient content at 1.5 m and 3.0 m relative to the values at row center (6.1 m) (B).

* Significant at $P < 0.1$, ** Significant at $P < 0.05$, *** Significance at $P < 0.01$

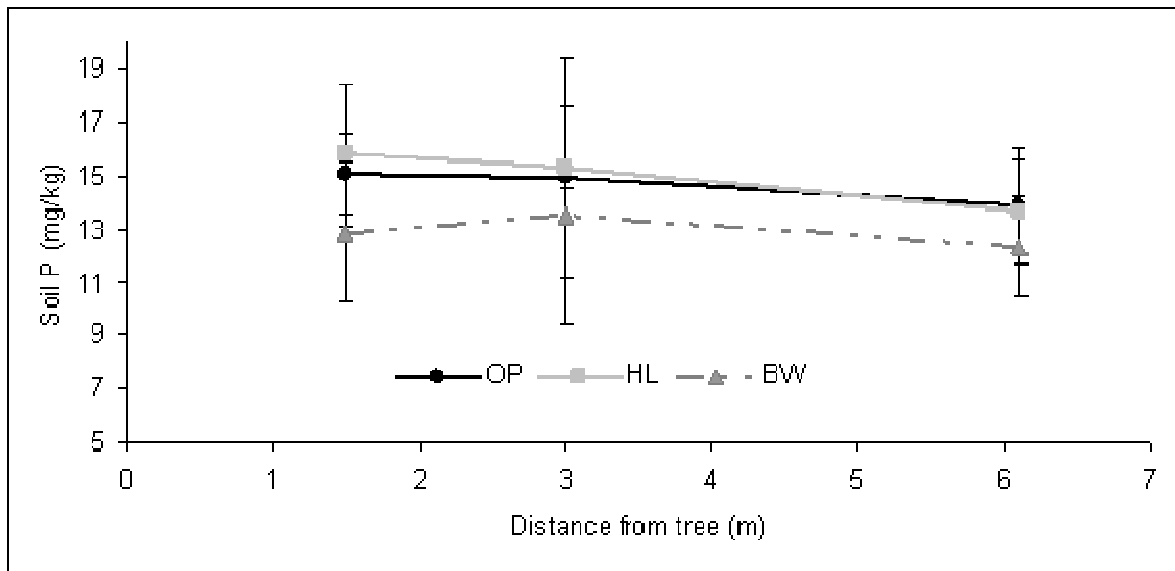


Figure III.7. Soil P content by treatment and distance, bars equal one standard deviation from the mean.

IV. Tree Effects on Forage Growth and Soil Water in an Appalachian Silvopasture

Abstract

Silvopastures have the potential to increase forage yields beneath trees. This ability has been attributed to a combination of factors including improved water use efficiency in shaded grass and increased water availability through hydraulic lift by trees. The objectives of this research were to determine if silvopastures changed forage mass production and available soil water, and to determine how these two factors were related. These factors were studied by pasture treatment and distance from the trees. Sampling of forage mass and soil water occurred at 1.0 m, 2.0 m, and 3.6 m from the tree stem, or plot center under honey locust (*Gleditsia triacanthos* L.), black walnut (*Juglans nigra* L.) and shade cloth in 2006 and 2007. Soil water was measured in the top 10 cm of soil using a capacitance type probe, and at 30 cm intervals, from 45cm to 105 cm, using a neutron probe. Forage was collected to determine dry mass and annual yield. In 2006, forage mass was greater under black walnuts and honey locusts than under 70% shade cloth. In 2007, with a 50% shade cloth, forage growth was similar in all treatments. Initial soil water content was lowest under shade cloth in 2006. In 2007 the rate of soil drying was lower under shade cloth compared to honey locust or black walnut. Similarities in forage mass between treatments in 2007 indicate that the differences in soil water were not biologically significant for forage growth. Lower forage mass under the 70% shade cloth in 2006 was due to suppressed growth from intense shading.

Introduction

Silvopastures are used by livestock producers to increase forage production and farm profits. Garret and associates (2004) reported that financial analyses of silvopasture systems in the southern US show consistently improved profitability compared to pure plantations or pure pasture systems. Clason (1999) found that the value of loblolly pine silvopastures compared favorably to loblolly pine plantations when the right forage was used; two of the three forage types in silvopastures in an experiment in Louisiana had a higher future net value than the pine plantation alone. Following a financial analysis of different agricultural systems, Husak and Grado (2002) concluded that silvopastures performed favorably against pastures, pine plantations, corn, soybeans, and rice, especially when hunting leases were incorporated in the overall farm enterprise. The multiple products produced by silvopastures also buffer producers against market fluctuations (Kurtz, 2000).

Optimizing production and value of silvopasture has been challenging because interactions between trees, forage and their environment are not well understood. Jose and collaborators (2004) reported that though many crop species tend to have reduced yield when shaded, yields of pasture species tend not to change or may even increase under moderate shading. In Virginia, Buegler and associates (2005) found a 20% increase in cool-season forage production under moderate tree cover and no change in forage production under heavy or light tree cover. Forage production was greater under black walnut (*Juglans nigra* L.) than honey locust (*Gleditsia triacanthos* L.). In West Virginia, Belesky (2005) observed the highest leaf mass in orchard grass under partial canopies with 40-70% shade compared to orchard grass that was open grown or growing under a full canopy with 90% shade. In north-eastern Australia, Durr and Rangel (2002)

observed a 90% increase in forage production under leguminous raintrees (*Samanea saman*) compared to adjacent open grasslands.

Reduced forage growth was observed when light was the limiting resource, on richer soils, and in cooler climates (Wilson, 1998). Burner (2003) found that tall fescue and a fescue/orchard grass mix performed best in the pasture and worse in silvopastures, but yield from pure orchard grass was greater in a loblolly pine silvopasture than in an open pasture. McGraw and collaborators (2005) found that alfalfa growth was reduced by 44% under black walnut in Missouri. Kallenbach and associates (2006) measured a 20% reduction in forage production in a hybrid pine-walnut silvopasture in Missouri compared to an open pasture, but animal performance was the same in the two systems. Research by Wanveterat and associates (2004) in Florida found that cotton lint production in a pecan-cotton alley crop without root barriers was reduced by 26% compared to a pecan-cotton alley crop with root barriers or cotton monocrop.

There is ongoing international research to determine the mechanisms responsible for changes in forage growth under trees. In a review of the literature Buresh and Tain (1998) reported that in sub Sahara Africa the adoption of agroforestry practices, such as woody fallows, helped small farmers by increasing soil nitrogen, reducing nutrient loss to leaching, and improving soil physical properties. Higher concentrations of soil C, nitrogen, and phosphorous have been observed in silvopastures and alleycrops in numerous studies in other parts of Africa and the world (Gindaba et al., 2005; Thevathasan and Gordon, 1997; Nair et al., 2007; Munoz et al., 2007). Shading has been found to increase forage yield for some species and decrease it for others, and the shading effects of the tree vary depending on species characteristics and relative position of the

tree to the forage, or other crop (Wilson, 1996; Belesky, 2005; Cruz, 1997; Kohli and Saini, 2003).

Silvopastures can also affect micro climate in beneficial ways. In a study in West Virginia, Feldhake (2002) found orchardgrass growing under 77% cover in a mixed pine silvopasture was less prone to suffer damage during radiant frost events because the forage temperature was up to 10.4°C warmer than open pastures on nights with a risk of radiant frost.

The release of juglone, an allelopathic chemical, will hamper or kill many plant species, but allow others to grow with reduced competition (Scott and Sullivan, 2007; Ercisli, 2005). In a study in Florida, Wanveterat and associates (2004) found that cotton lint yield in a pecan-cotton alley crop with root barriers was higher than in a pecan-cotton alley crop without root barriers. This yield difference was attributed to allelopathy even though soil concentrations of juglone were not measured. Allelopathic effects can go both ways: in a greenhouse study by Picon-Cohard and associates (2001) walnut seedling growth was adversely affected by ryegrass compared to walnut monocultures, but ryegrass was not adversely affected by the walnut seedlings.

The extent to which hydraulic redistribution of water affects forage growth and productivity is uncertain. In Utah, Leffer and associates (2005) found that senesced cheatgrass (*Bromus tectorum*) increased the rate of rewetting in subsurface soil horizons compared to plots cleared of vegetation. In Oregon, Brooks and associates (2002) observed nightly rewetting of soil under ponderosa pine (*Pinus ponderosa*) by hydraulic lift with sufficient water to supply the trees with 21% and 29% of their daily water use at 20-60 cm and 60-100 cm respectively. Corak and associates (1987) found that a corn

(*Zea mays*) plant was able to survive when it's only source of water was transferred by the root system of an alfalfa (*Medicago sativa*) plant under simulated drought conditions, the presence of hydraulic lift was then confirmed by watering the alfalfa with deuterium labeled water then measuring the corn for elevated deuterium levels. Throughout the study, there were no measureable changes in soil water due to hydraulic lift. In north-east Spain, Peñuelas and Filella (2003) supplied a root of a *Pinus nigra* tree with deuterium labeled water and found that surrounding plants had increased foliar deuterium concentrations indicating hydraulic lift by the pine and water parasitism of surrounding plants. In a Texas savanna Zou and associates (2005) found that the removal of trees increased water stress on shallow rooting plants but not deep rooting ones. The degree to which hydraulic lift improves crop growth is uncertain, Ludwig and collaborators (2004) found that under *Acacia* trees in east Africa soil water and forage growth increased after root trenching, showing that any potential benefits of hydraulic redistribution were negated by increased water usage by the trees.

Interactions between trees and forages can lead to improved resource use. Levesley and associates (2004) found higher soil water storage under maize monocultures than in senna-maize or gevillea-maize alley cropping systems. Using stable isotopes in a study in a savanna in Arizona, Weltzin and McPherson (1997) found that most of the water uptake by Emory oaks over two years old was from deeper soil horizons not accessed by associated bunchgrass. Lefroy and Stirzaker (1999) concluded that the inclusion of ally cropping systems into the grain producing areas of southern Australia could prevent increased salinity in land under cultivation by increasing water utilization. In Argentina, Fernadez and associates (2008) observed partitioning of soil

water usage between ponderosa pine and mixed grasses where 75-90% of the water used by grasses came from the upper 20 cm and less than 20% of the pine's water came from the same layer. In northern Kenya, Lehmann and associates (1998) found complementary interactions between sorghum and *Acacia saligna* where crop roots dominated the surface soil between tree rows, and trees accessed water deep in the soil profile, allowing for more complete utilization of water resources on the site.

In the Ridge and Valley province of Virginia, tall fescue and orchardgrass are the dominant pasture grasses. Studies have found greater growth of these grasses under partial shade (Buerger et al., 2005; Belesky, 2005). This experiment was designed to test the hypothesis that hydraulic redistribution of water from trees to the forage would promote increased forage growth. The first objective of this study was to determine if the inclusion of black walnut (BW) and honey locust (HL) into a pasture changes the distribution of soil water for increased forage production compared to that under shade cloth (SC). If trees do influence soil water and forage production, the second objective was to determine if changes in forage production are correlated with changes in soil water from the effect of the different tree species.

Methodology

Experiment location and design

The research site is located 10 km southwest of Blacksburg at 37° 11' N latitude and 80° 35' W longitude, in the Ridge and Valley province of Virginia at an elevation of 545 m. The site is on toeslope and sideslope of the lowest of a series of old river terraces deposited by the New River. The soils on the slopes (7-25%) are classified as Unison and Braddock fine, mixed, semiactive, mesic Typic Hapludults. In the bottoms, the soils

are predominantly Rayne fine-loamy, mixed, active, mesic Typic Hapludults (Cregger and Hudson, 1985). Rainfall is evenly distributed throughout the year averaging 1000 mm annually. The temperature, precipitation, and ground level radiation for Kentland farm in the 2006 and 2007 growing seasons are depicted in figures IV.1 and IV.2.

Black walnuts and honey locusts silvopastures were established in existing cool season grass pastures in 1995. Fertilizer was applied in the fall of 2004 with 60 kg urea, 40 kg super-concentrated phosphate, and 50 kg KCl per hectare, and again in the spring of 2007 with 30 kg N ha⁻¹ as urea. The site was mowed intermittently during the summer months and the grass was left to decompose on site. To determine the allocation of soil water between the trees and forage grasses, nine 7.2-m by 6-m pasture plots were chosen. Three plots had a black walnut (BW) tree at their center, three had a honey locust (HL) at their center, and three were in open areas over which shade cloth (SC) tents were erected. Trees of similar heights and canopy diameters were chosen. Shade umbrellas were 6.1-m by 6.1-m squares suspended 3 m above the ground at their center on a steel pipe. Their canopies were secured by ropes at their corners and were 1.5 m above ground at their edge. The canopy of the umbrellas was formed from black shade cloth that intercepted 70% of the sunlight in 2006. In 2007 a 50% shade cloth was used to better match light levels under the tree canopies. The SC plots were used as the controls to determine if differences in forage growth under tree canopies were the result of factors other than shading.

This field plot study was designed as a randomized block design with three replications (blocks) of three treatments. Trees were planted in rows at a 7.2-m spacing. Measurements were taken at 1, 2, and 3.6 m up and down slope from the center of each

plot (Figure IV.3). This design allowed measurements of soil water and forage yield with increasing distance from the trees. The 2-m measurement point was under the canopy dripline and the 1-m point was halfway between the dripline and tree stem. Forage measurement plots (2.00 m X 0.56 m) were adjacent to the soil water measurement points at 1 m, 2 m, and 3.6 m from the tree or plot center (Figure IV.3).

Soil water measurements

Soil volumetric water content (θ_{vol}) from the 0-10 cm soil layer was measured every half hour. Measurements were collected using 10 cm long capacitance-type soil water sensors (EC-10 soil moisture probes, Decagon, USA) five of which were connected to each data logger (Em-5, Decagon, USA). Sensors were installed using a knife to open a narrow slit in the soil into which the sensors were placed before the slit was pressed closed. After the probes were in place, their wires were covered with PVC tubing to protect them from animal and mowing damage. The data logger only supported five sensors so only one of the 2.0-m measurement points in each plot was randomly selected to have a sensor. Sensor data for the 1.0-m and 3.6-m positions were averaged for the plot value. Soil samples were collected from the top 10 cm of soil in the area around the sensors using a soil core sampler. These soil samples were weighed before and after drying to a constant weight at 105°C to calibrate the sensor data.

Values for θ_{vol} at 45 cm, 75 cm and 105 cm was measured using a neutron probe (Model 4300 depth water gauge, Troxler, USA). Holes into which aluminum access tubes were installed were dug up to 1.5 m deep using a manual auger, or a hydraulically driven auger where soils were cobbly. Soil removed during the augering process was separated by horizon and collected in paper bags. The collected soils were used to

backfill the area around the neutron probe tubes, by horizon, to minimize discontinuities between the tube and surrounding soils. Access tubes were sealed by placing a rubber stopper in the bottom of the tube. Where shallow soil and rockiness precluded digging to 1.5 meters, the holes were dug as deep as possible and the neutron probe tubes were cut to fit the depth of the hole. Neutron probe readings were calibrated by collecting soil cores at a depth of 30 cm using a soil core. These soil samples were weighed before and after drying to a constant weight at 105° C to calibrate the sensor data.

Forage measurements

Predawn plant water potential (Ψ_{forage}) measurements of the fescue forage crop were collected using a pressure bomb (Model 600 pressure chamber instrument, PMS Instrument Co., USA). Measurements were made on overcast nights without rain to avoid aberrant measurements caused by dew. Plant water potential was measured using the youngest fully expanded leaf of a fescue plant within each forage plot. Correlating Ψ_{forage} with soil water potential (Ψ_{soil}) under trees and shade cloth was meant to test for forage access to hydraulically lifted water.

Forage samples were harvested every 30 to 60 days to a height of 7.5 cm in 2.00 by 0.56 m sampling plots. Harvests were accomplished by first mowing the strip of vegetation along the sides of the plot to prevent contamination, then plots were mowed using a rotary mower with bagger and the clippings were collected. The vegetation samples were then oven dried at 65°C to constant weight before weighing.

Light

Photosynthetically active radiation was measured twice during the growing season using a light meter (LI-250A Light Meter, LI-COR, United States). The extent of

shading was then estimated by projecting the location of the shadows of the shade cloth and tree and surrounding trees on the forage measurement plots throughout the day and growing season. Daily light interception was calculated by multiplying the trees' average light interception by the percent of the day that a forage plot was shaded, then adding the percent of the day that the forage measurement plot was unshaded. Plot-wide light interception values were an average of the light interception values from the individual forage measurement plots.

Statistics and data analysis

The θ_{vol} values collected via the neutron probes (45-105 cm) and capacitance type probes (0-10 cm) were calibrated prior to analysis. This was done by pairing θ_{vol} values from soil cores to the measurements from the neutron probe or capacitance probes taken at the same time. A linear regression was then performed on the paired data and the resulting models were used to correct the data collected from the associated θ_{vol} measurement device.

The half-hourly surface soil (0-10 cm) θ_{vol} data were averaged by 12-h blocks to create data sets with two daily averages of θ_{vol} . For analytical purposes, only the dry down periods of the data were used (Figures IV.4A, IV.4B, and IV.5). Each block X treatment X distance combination was analyzed separately by using the dry-down periods (experimental unit) across the growing season (example Figure IV.6A) to create a composite relationship of θ_{vol} as a function of the number of days since rewetting (Figure IV.6B). A regression was then performed on the data set for each block X treatment X distance to determine the slope and intercept values (b_1 and b_0) of θ_{vol} as a function of the days since rewetting for the growing season. The slope and intercept values are the basic

experimental units representing the rate of soil drying (b_1) and the initial soil water content (b_0). The regression shown in figure IV.6B is an example of the calculation of one experimental unit.

Soil drying rate and initial soil water content were analyzed using a split plot ANOVA experiment where blocks were replications, pasture treatments were the main plot effect, and distance from the tree or plot center was the sub plot effect. Both the 2006 and 2007 data were analyzed in the same manner; however, the 2007 data were transformed using the equation $y=-1/x$ prior to performing the regressions because the longer dry-down periods in 2007 resulted in a curvilinear dry-down response.

A water release curve was produced for the surface soil data to transform θ_{vol} into Ψ_{soil} . The curve was created by weighing soil cores at 0, 0.033, 0.1, 0.2, and 0.3 MPa, then oven drying the cores to determine θ_{vol} . A nonlinear regression was then run to create an equation representing the Ψ_{soil} as a function of θ_{vol} . The fit statistics for the nonlinear regression were determined by running a linear regression on the predicted and residual values from the nonlinear regression.

To test for hydraulic lift, comparisons between Ψ_{soil} and Ψ_{forage} were made by plotting the Ψ_{forage} values against the average Ψ_{soil} value for a given treatment and distance. Direct comparisons between Ψ_{soil} and Ψ_{forage} for a given point were not possible due to missing θ_{vol} values during collection periods. After Ψ_{soil} and Ψ_{forage} values were paired, a linear regression of the data was performed for each treatment, and then an ANOVA of the slope values were used to test treatments for significant differences in the relationship between Ψ_{soil} and Ψ_{forage} .

Neutron probe data were analyzed as an ANOVA split plot design. Treatments were whole plots, and time, distance and depth were subplots. Annual forage growth was analyzed as a split plot with pasture treatments as main plots and distance as a subplot.

Evidence for hydraulic lift from deep soil layers to the surface soil (0-10 cm) was collected by randomly selecting three days during draw-down periods and examining the 30 minute interval data for any increases in θ_{vol} during a given day that could be attributable to hydraulic lift. When increases occurred, the time of the start of the increase and the peak of the increase were recorded. The magnitude of the change was determined by subtracting the start time θ_{vol} from the θ_{vol} at the time of the peak. Any increase in θ_{vol} less than 1% fell below the sensitivity level of the sensor.

Results

Weather

Weather conditions in 2006 and 2007 were different. There was 39% more rain and 21 more days during which it rained between April 1st and September 30th in 2006 than in 2007 (48.1cm vs 34.7cm). Greater cloudiness between April 1st and September 30th in 2006 meant that it had 9% less ground level radiation than 2007.

Forage growth

In 2006 BW and HL plots had significantly higher forage growth than did the 70% SC plots (Figure IV.7). Lower forage growth in the SC plots was limited to the areas under the shade cloth (forage gathered at 1 m and 2 m) and there was no difference between the mass of forage grown outside of the shade cloth (3.6 m) and that of the forage grown in the BW or HL plots. For the 2007 growing season, the 70% shade cloth was replaced with a 50% shade cloth to better simulate the degree of shading provided by

the trees. In 2007, there were no significant effects of treatment or distance on forage growth (Figure IV.8), but compared to 2006, total forage growth in 2007 was lower in the HL and BW plots and higher in the SC plots.

Light

Shade intensity provided by the tree canopy or shade cloth was greater under HL (58%) than BW (51%) and lowest under 50% SC (2007). The cumulative shading of all forage plots over the course of a day was greatest in SC plots where 33% of sunlight was intercepted and lowest in BW plots where 25% of the light was intercepted. Total daily light interception by the tree canopies decreased with distance from the HL trees (33% interception at 1.0 m, 27% interception at 2.0 m and 25% interception at 3.6 m) and BW (29% interception at 1.0 m, 24% interception at 2.0 m and 22% interception at 3.6 m). For SC plots, daily light interception was the same at 1 m and 2 m (50% interception) and there was no light interception at 3.6 m.

Soil water

There was significantly lower initial soil water content under 70% SC than under HL or BW in 2006 (Figure IV.9 and Table IV.1). In 2007, initial soil water content was similar between pasture treatments (Table IV.1). The forage under SC had a lower soil drying rate than the HL or BW silvopastures (Figure IV.10). Initial soil water content in 2007 was also lower at 1 m from the tree, or plot center than, than at 2 or 3.6 m, but there were no interactions with silvopasture treatment (Figure IV.10, Table IV.1).

Volumetric soil water content from 45 cm to 105 cm was similar among treatments (Table IV.2). Values for θ_{vol} increased with depth and distance from tree or SC plot center, but there were no significant depth by distance interactions (Figure

IV.11). Time, and time interactions, were small and did not seem to be important to these pasture systems, or relevant to this experiment (Table IV.3, Figure IV.12).

Two tests were performed to determine if hydraulic lift was occurring on the site. First, the 30 minute increment data from the top 10 cm of soil was examined for increases in θ_{vol} . Only two sampling position X day combinations of 136 sampling point X day combinations investigated had an increase in θ_{vol} that $\geq 1\%$. One event started at 8:30 AM and peaked at 3:00 PM with a maximum increase of 1% (Figure IV.13). The other event began at 7:30 PM and peaked at 8:30 PM and there was no subsequent decrease in θ_{vol} . The other test for hydraulic lift was to compare Ψ_{forage} and Ψ_{soil} between treatments to determine if the forage HL and BW plots had access to water unavailable to the forage in the SC plots. Regression showed that Ψ_{forage} values were correlated with Ψ_{soil} values (Figure IV.14A,B,C). As expected, the slopes of all regressions were less than the 1:1 Ψ_{soil} to Ψ_{forage} ratio that would have occurred if Ψ_{forage} were at equilibrium with only the top 10 cm of soil because the forage roots had access to soil water at depths greater than 10 cm. A T-test was used to compare the slopes of the regressions for HL and BW against that of the SC plot. The regression slope for the HL plots was significantly greater than the slopes for the regressions of BW and SC plots, but the regressions' slopes for the SC and BW plots were similar (Figure IV.14D).

Discussion

In 2006 greater forage growth beneath BW and HL compared to the 70% SC treatment was likely due to over shading. Forage growth was 30% lower under 70% shade (1 m and 2 m sampling points) compared to the unshaded (3.6 m sampling points) grass in the same SC plots. There were no treatment effects or differences in growth

within the SC plots when the 50% shade cloths were used the following year. Similar trends in the response of fescue growth to shade were seen in a pot study by Allard et al. (1991) where fescue grown under 70% shade produced almost 25% less dry leaf mass than fescue that was grown in full sun or under 40% shade.

In 2006 initial soil water content was lower in the 70% SC plots compared to the HL or BW plots. It's likely that the difference in initial soil water content in 2006 was due to the intense shade produced by the 70% SC, which lowered evapotranspiration by the grasses. The shade also suppressed grass growth which further decreased evapotranspiration and water use. Higher use of water by the trees in the HL and BW plots could also be responsible for some differences measured, but any effect would be minor because in 2007, when 50% SC plots were used, initial soil water content and forage growth was similar among all treatments.

Higher rates of soil drying in HL and BW plots than SC plots in 2007 are likely due to the presence of trees and differences in shading. The shade from the 50% SC was not intense enough to suppress forage growth, but it would have decreased the evapotranspiration of the forage compared to forage grown in the less shaded HL and BW plots. Tree roots under the root systems of the grasses could also cause the site to dry faster and more completely as the trees absorb the water that moved past the grasses and decrease the potential for rewetting from capillary rise.

The hypothesis that hydraulic lift into the top 10 cm of soil was occurring on these sites was not supported. Comparisons between predawn Ψ_{soil} and Ψ_{plant} as a means to determine the presence of hydraulic lift did not provide evidence of hydraulic lift. If Ψ_{plant} was lower under trees than in SC plots while Ψ_{soil} remained the same that would

have indicated that forage beneath trees had access to water unavailable to the SC forage, potentially through hydraulic lift. This method was used because in several experiments investigators were unable to measure water changes in soil due to hydraulic lift even though plant survival and labeled water provided evidence of hydraulic lift (Corak et al., 1987; Hirota et al., 2004). Regressions of Ψ_{soil} to Ψ_{forage} failed to indicate the presence of hydraulic lift on our study sites since neither HL nor BW were significantly different from the SC (Figure IV.14D). Regressions of the relationship between Ψ_{soil} and Ψ_{plant} for all pasture treatments had slopes significantly less than one, but forage access to soil water below the depth measured by the capacitance probes (0-10 cm) was probably the reason.

Increases in θ_{vol} in the top 10 cm of soil that suggested hydraulic lift were measured by approximately half the capacitance probes, but these patterns were independent of pasture treatment and distance from tree. Only two sample days had increases in θ_{vol} over 1% (the lower limit of sensitivity in the probes used) indicating that most increases were measurement artifacts rather than an actual phenomenon. One of the two measurement days increased by 1% θ_{vol} abruptly and immediately leveled off, indicating that the increase in θ_{vol} was not due to hydraulic lift. The other measurement day had a hump-shaped 1% θ_{vol} increase in the middle of the day (Figure IV.13). Since it was a lone event (1 occurrence out of 136 observations) and the change in θ_{vol} seemed to correspond to ground level radiation readings it seems that temperature sensitivity in the decagon ec-10 soil water probes are a likely cause for the increase (Campbell, 2006). However, daytime increases in soil water have been reported by several other authors (Fernández et al, 2008; Millikin Ishikawa and Bledso 2000; Espeleta et al., 2004; Yoder

and Nowak, 1999). Fernández and associates (2008) measured diurnal increases under ponderosa pine and suggest that it was due to water release from roots following evaporation of water from the soils surface. Milkin Ishikawa and Bledsoe (2000) observed daytime increases in soil water readings in late summer at low soil water levels. They attributed these increases to overcorrection for changes in soil temperature. In South Carolina Espeleta et al. (2004) observed daytime hydraulic lift, which they hypothesized was due to stomatal closure in the afternoon. Yoder and Nowak (1999) observed daytime hydraulic lift in crassulacean acid metabolism plants in the Mojave dessert which they attributed to the plants closing their stomata during the day and opening them at night, the opposite of most plants.

If hydraulic lift had occurred, increases in θ_{vol} in the top 10 cm of soil would have been expected at night when trees were not transpiring, with θ_{vol} total peaking at dawn (Ludwig et al., 2003; Bauerle et al., 2008), and an increase in surface θ_{vol} should have been highest near the tree and lower with increasing distances from the tree (Dawson, 1993). However, competition with the root systems of the forage cover could cause a lack of tree roots in the top 10 cm thereby preventing measureable changes in soil water (Fernandez et al., 2008; Lehmann et al., 1998).

Soil water at 45cm, 75cm and 105 cm was predicted to show evidence of higher total water demand and higher water use rates for the HL and BW plots compared to the SC plots. Soil volumetric water content was also expected to increase with distance from the tree and be similar for all distances under the shade cloth, but there were no distance X treatment interactions. These findings contradict those of Green and Clothier (1999) who measured decreased water use with increasing distance from lone apple trees (*Malus*

domestica) where measurable changes extended 2 m from the trunk in the upper 60 cm of soil. The lack of difference in the study could have been due to topographic or tree effects. The research plots were on a floodplain and the sideslope of a low terrace below several higher terraces. Subsurface water from the higher terraces could have recharged the soil water content on site fast enough to offset the uptake by the trees. Different rooting patterns under HL and BW compared to apple trees may have meant that the measurement points were too far from the tree, or too deep in the soil to measure the water uptake by the trees.

Conclusion

Though the presence of trees did provide some shade to forage and increased water use in the plots, there was no indication that the presence of trees affected forage growth in either 2006 or 2007. The hypothesis that hydraulic lift was occurring on the site was not supported by changes in θ_{vol} measured by the capacitance probes or comparisons of plant and soil water potentials. Forage growth was similar in all treatments in 2007 and the lower forage growth under the 70% shade cloth in 2006 was attributed to excessive shading. The lack of treatment or distance effects on forage growth meant that correlations between soil moisture and forage growth would have been meaningless. Since the presence of trees was not detrimental to forage growth, then other benefits of a silvopasture, such as improved animal health and weight gain, and revenue from timber, nut, or fruit crops, provide strong economic incentives for adopting silvopastoral practices.

Table IV.1. ANOVA table for the regression lines from the volumetric water content for the top 10 cm of soil. “Initial soil water content” denotes the intercept for the regression which should correspond to treatment differences in tree and forage demand for water. “Soil drying rate” denotes the slope of the regression line as a proxy for the rate of water usage by the trees and forage.

	DF	2006		2007	
		Initial Soil Water Content	Soil Drying Rate	Initial Soil Water Content	Soil Drying Rate
treatment	2	0.0075***	0.2185	0.9866	0.0085***
block	2	0.1637	0.4165	0.393	0.7357
distance	2	0.6345	0.3511	0.1056*	0.2677
treatment*distance	4	0.2864	0.3106	0.406	0.1451

Table IV.2. Analysis of variance and source table for soil volumetric water content from depths of 45cm to 105 cm with time as a component. Though time was significant it was ignored due to the lack of treatment by time interactions or any ecologically important differences with time.

	df	p value
treatment	2	0.9218
block	2	0.152
depth	2	<0.0001***
treatment*depth	4	0.5059
distance	2	0.1117
treatment*distance	4	0.368
depth*distance	4	0.5549
treatm*depth*distan	8	0.3255
week	9	<0.0001***
distance*week	18	0.9681
treatment*week	18	0.0105
depth*week	18	<0.0001***
treatme*distan*week	36	0.8307
depth*distance*week	36	0.9435
trea*dept*dista*week	108	0.7942

Table IV.3. Analysis of variance and source table for soil volumetric water content from depths of 45cm to 105cm.

	df	p-value
treatment	2	0.9258
block	2	0.1534
depth	2	<0.0001***
treatment*depth	4	0.5054
distance	2	0.1005*
treatment*distance	4	0.3649
depth*distance	4	0.5241
treatm*depth*distan	8	0.2859

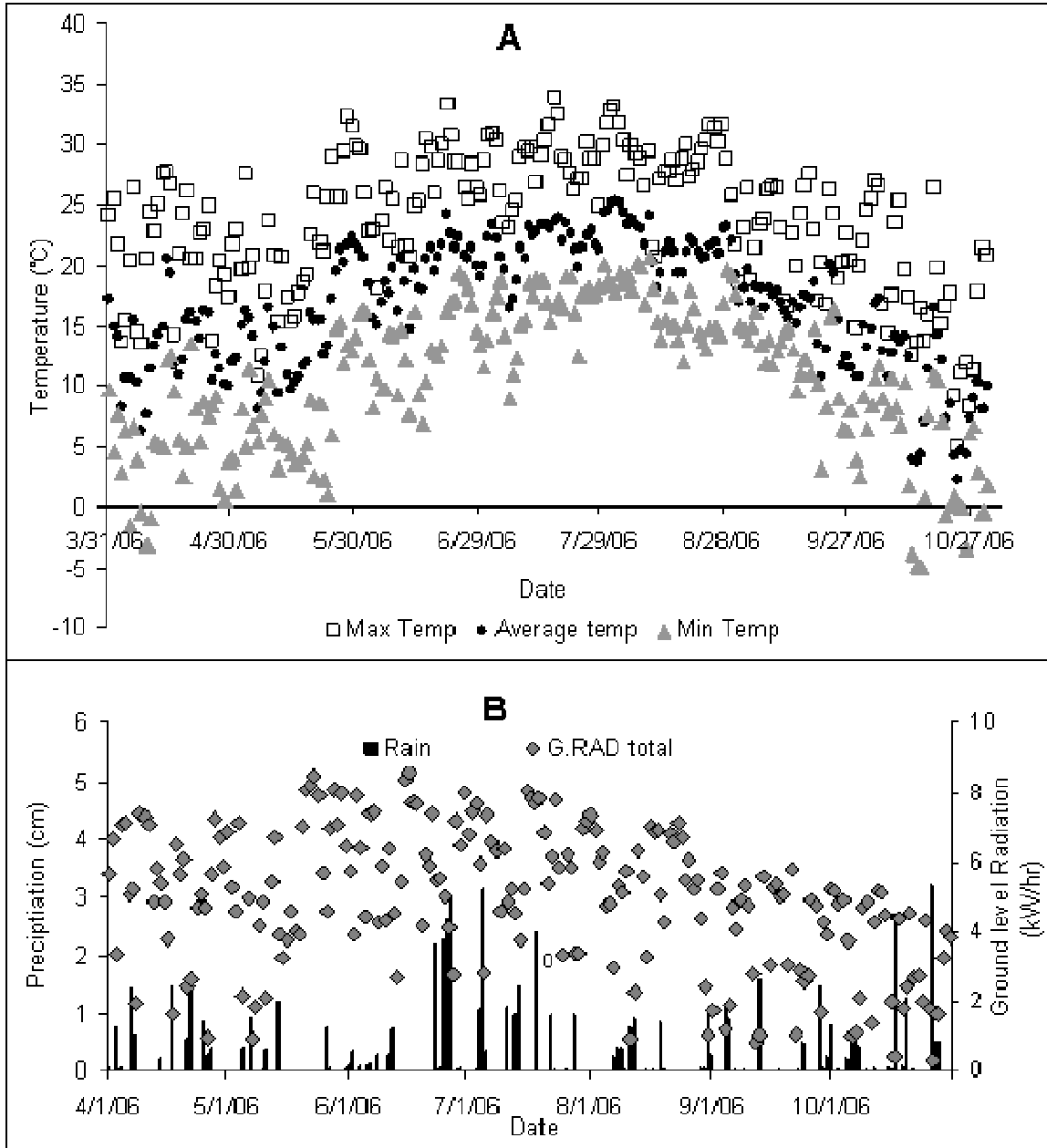


Figure IV.1. 2006 weather data from April 1st to October 31st. Maximum (Max Temp), average (AverageTemp), and minimum (Min Temp) daily temperatures are depicted at the top (A). Total daily precipitation (Rain) and ground level radiation (G.RAD total) are depicted in B.

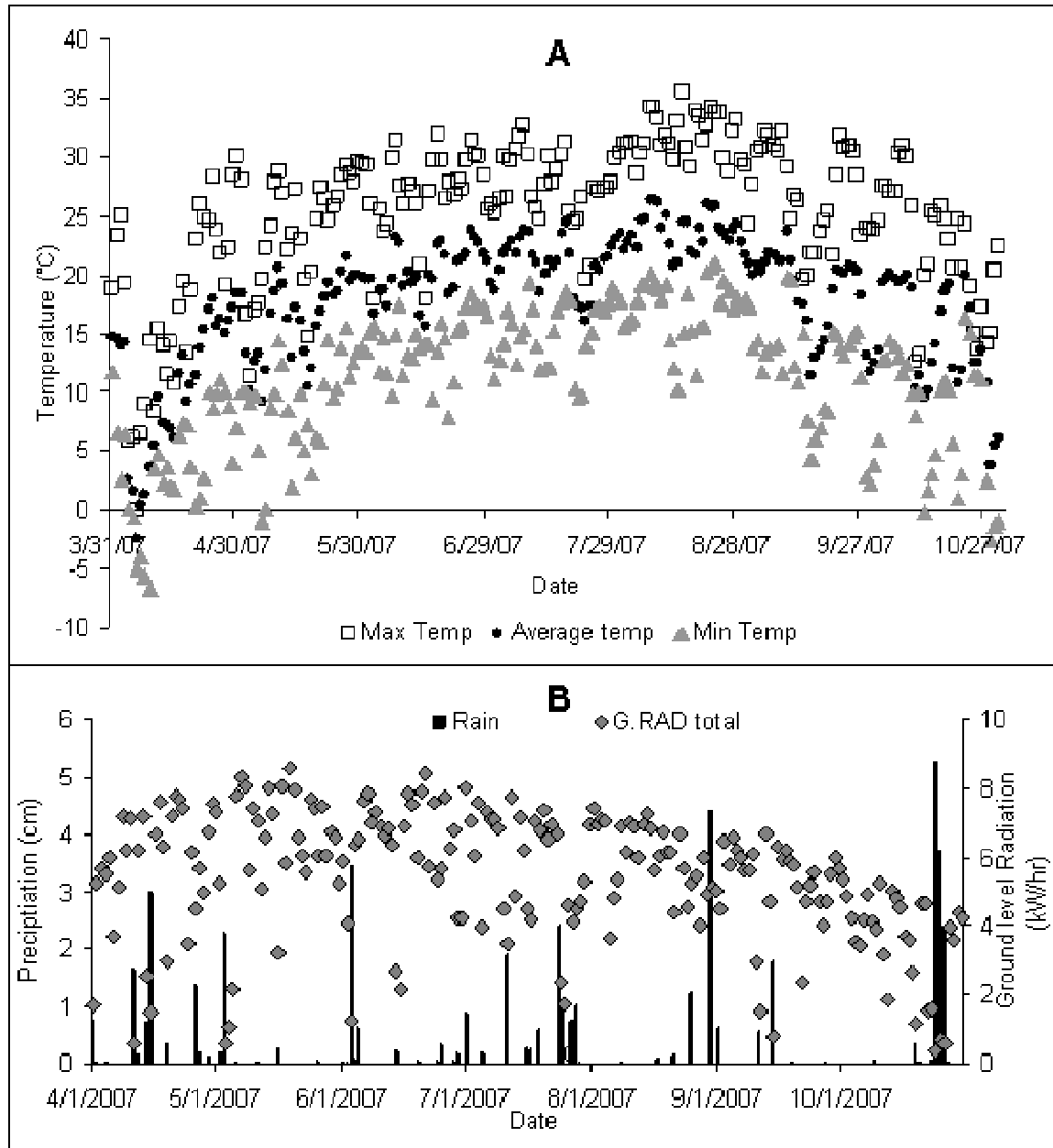


Figure IV.2. 2007 weather data from April 1st to October 31st. Maximum (Max Temp), average (AverageTemp), and minimum (Min Temp) daily temperatures are depicted at the top (A). Total daily precipitation (Rain) and ground level radiation (G.RAD total) are depicted in B.

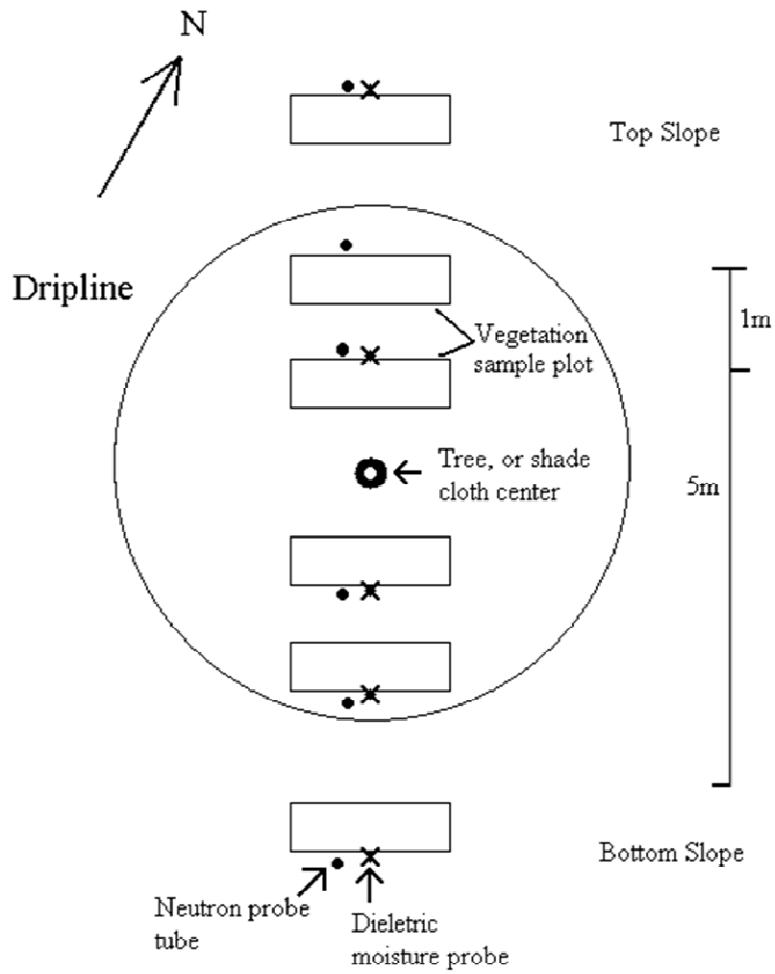


Figure IV.3 . Idealized and sampling design for the resource allocation study plots, depicting the orientation of the plots in the landscape and the distribution of sampling points and instrumentation.

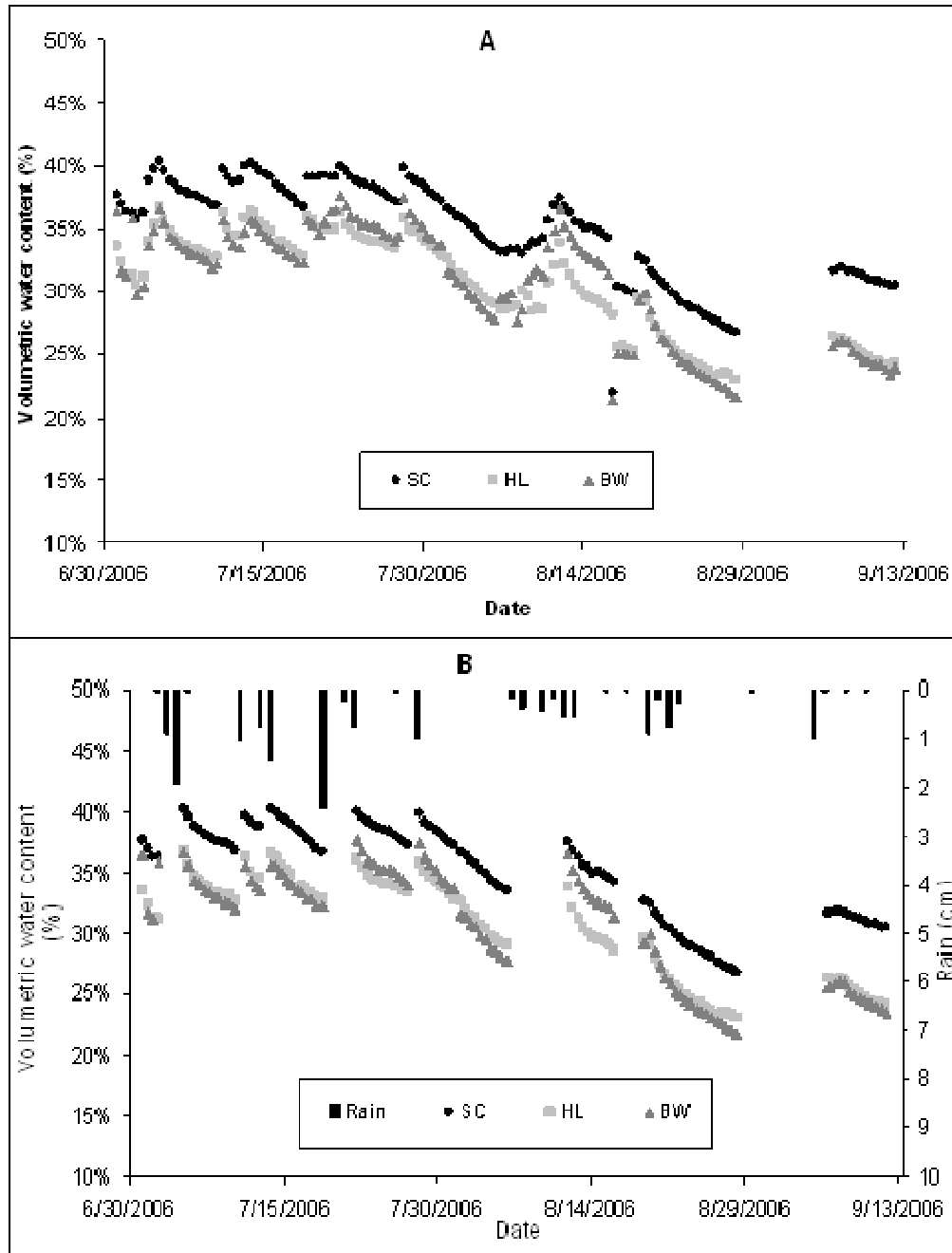


Figure IV.4. 2006 volumetric water content in the top 10 cm of soil under shade cloth(SC), honey locust (HL) and black walnut (BW). Values are averaged across block and distance from tree, or shade cloth center (A), and the same data with only the draw-down periods shown (B).

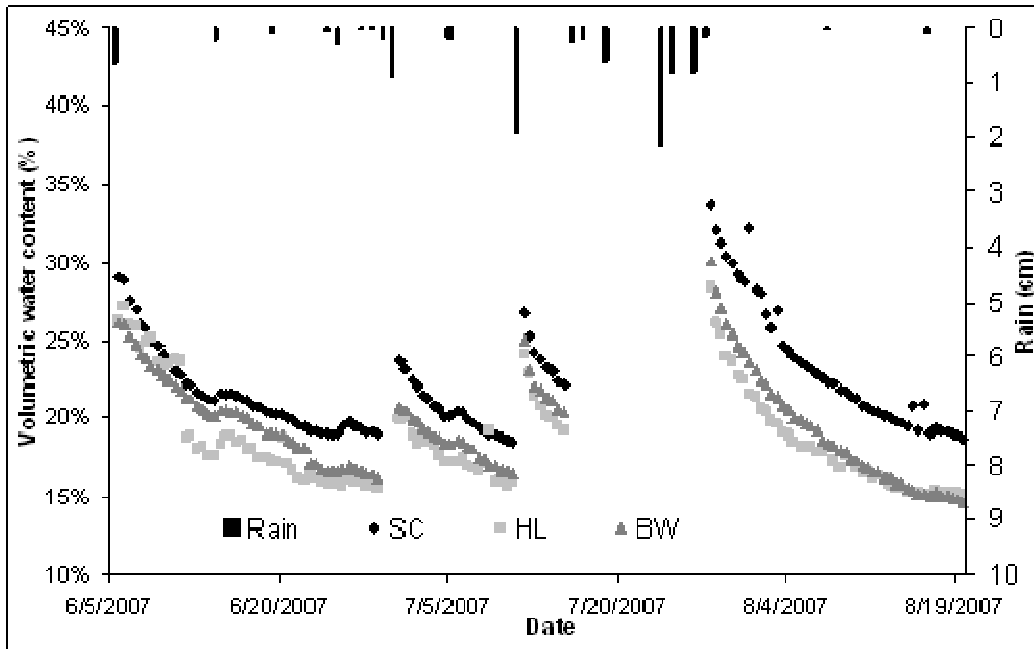


Figure IV.5. 2007 volumetric water content of top 10 cm of soil during draw-down periods in the summer under shade cloth(SC), honey locust (HL) and black walnut (BW). The values have been averaged across block and distance from tree, or shade cloth center.

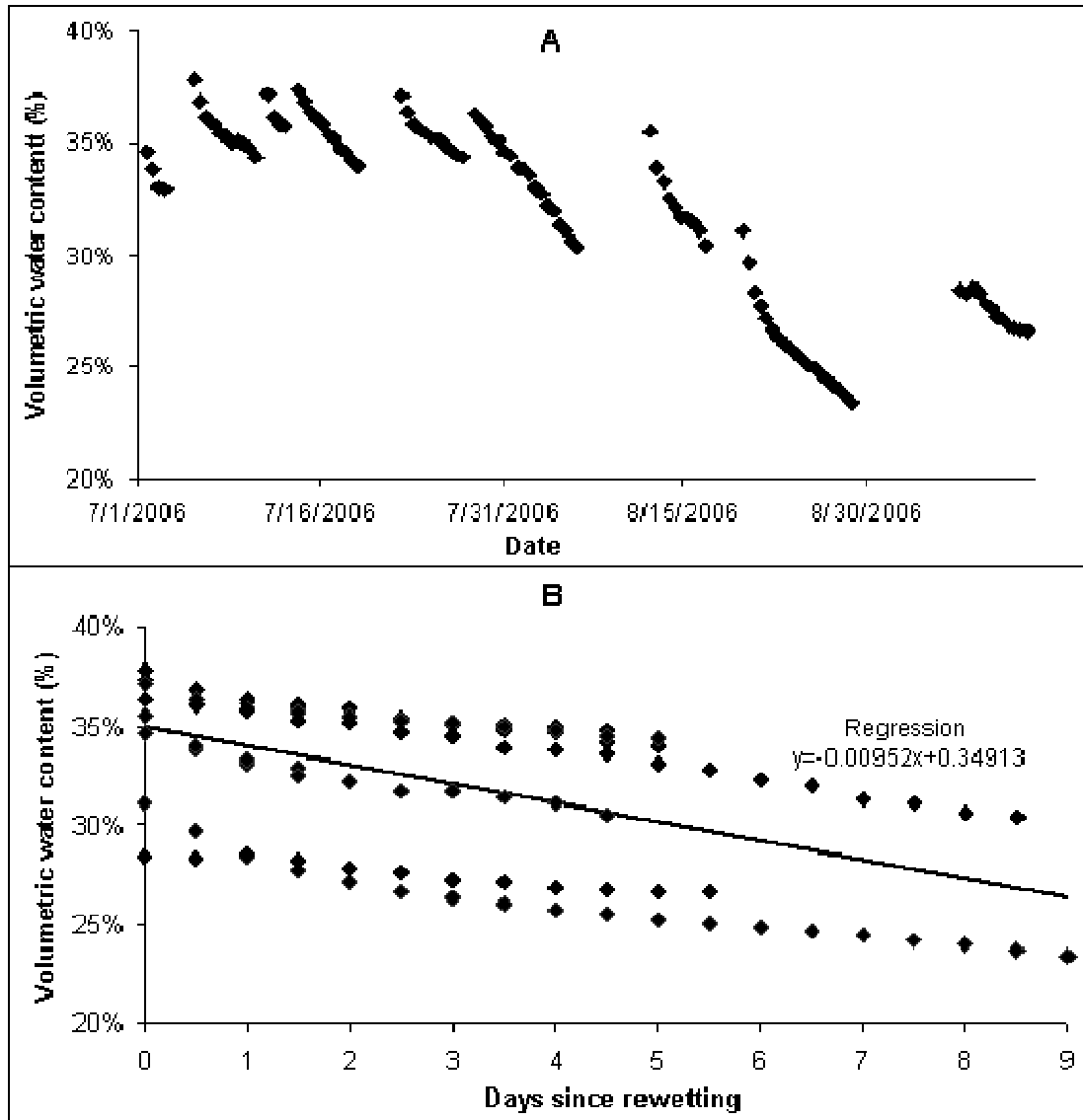


Figure IV.6. Volumetric water content in the top 10 cm of soil at 1 meter from the honeylocust in block 1 in 2006 shown by date (A) and as time since rewetting (B). Regressions were run for each of the 27 block by distance by treatment combinations in both 2006 and 2007.

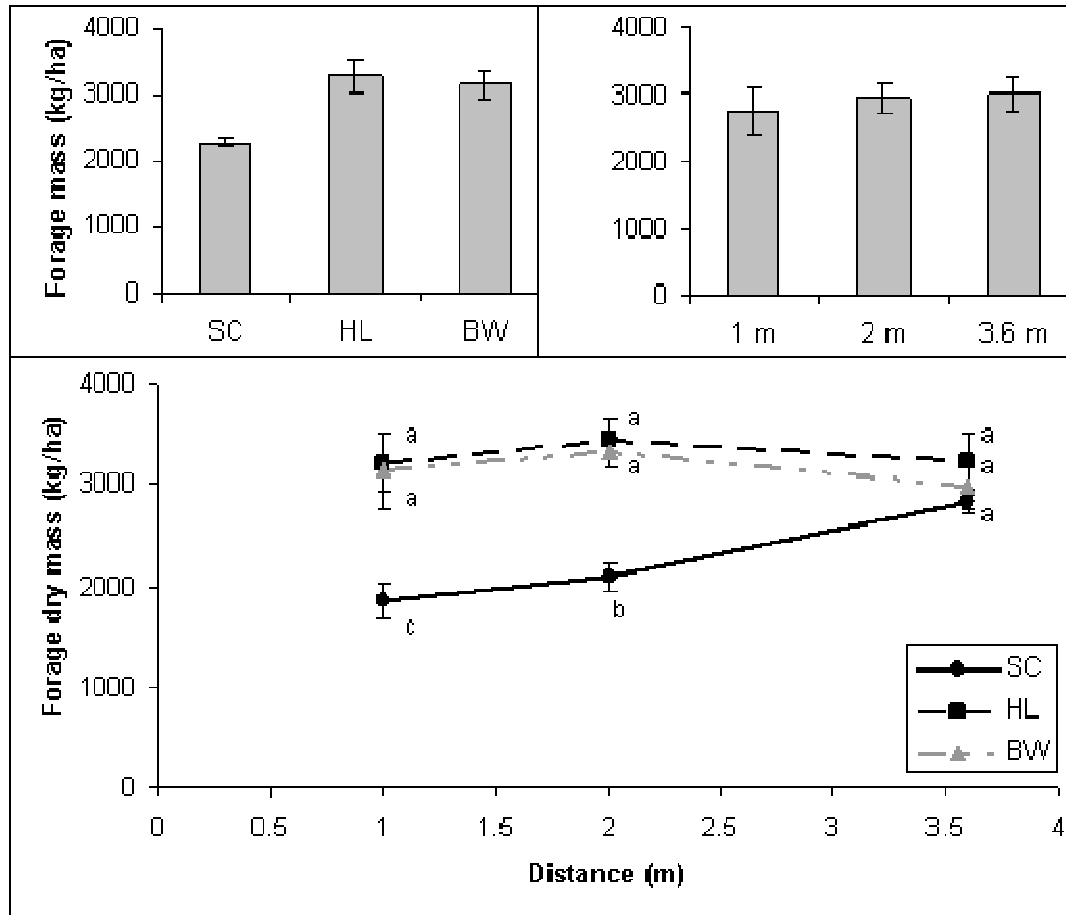


Figure IV.7. Total forage production in 2006 under shade cloth(SC), honey locust (HL) and black walnut (BW) averaged across blocks by treatment and distance from tree, or the center of the shade cloth plots. 70% shade cloth was used cover the shade cloth plots in 2006. Bars represent one standard deviation from the mean and points with the same letter are not significantly different.

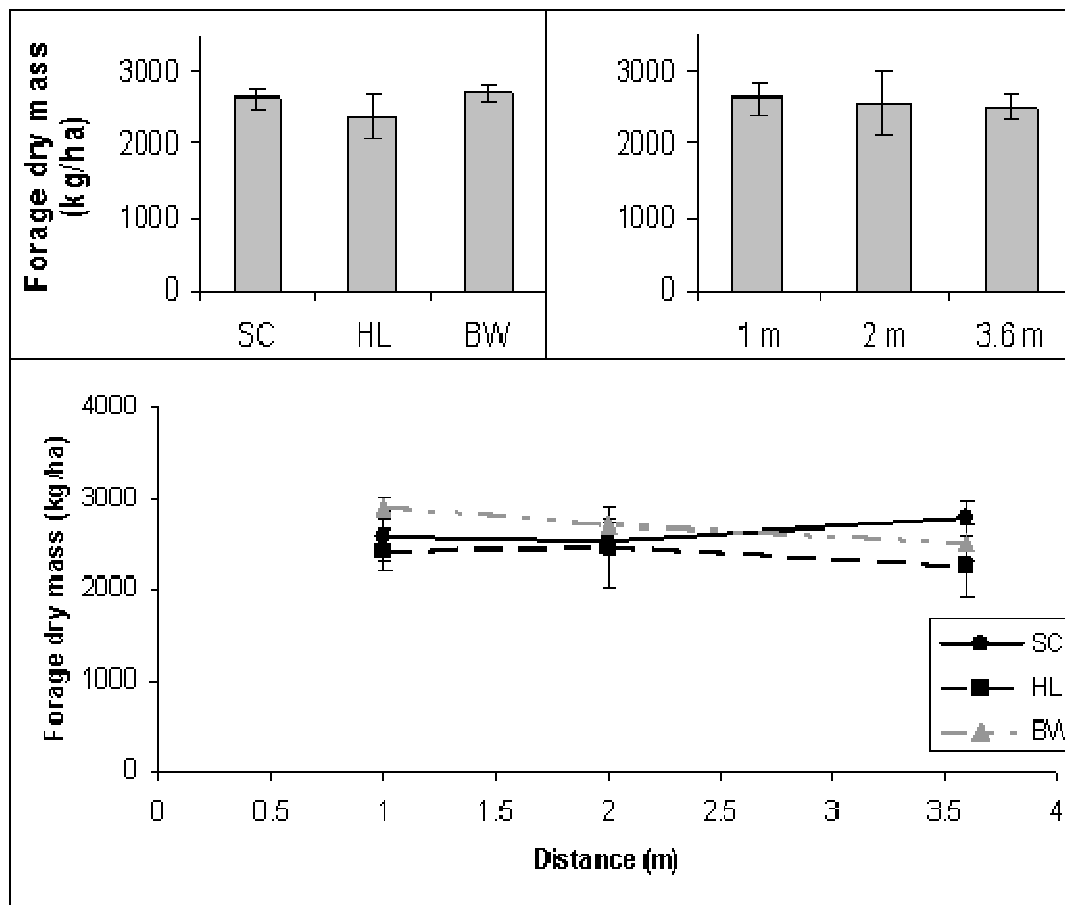


Figure IV.8. Total forage production in 2007 under shade cloth (SC), honey locust (HL) and black walnut (BW) averaged across blocks by treatment and distance from tree, or the center of the shade cloth plots. 50% shade cloth was used to cover the shade cloth plots for the 2007 growing season. Bars represent one standard deviation from the mean.

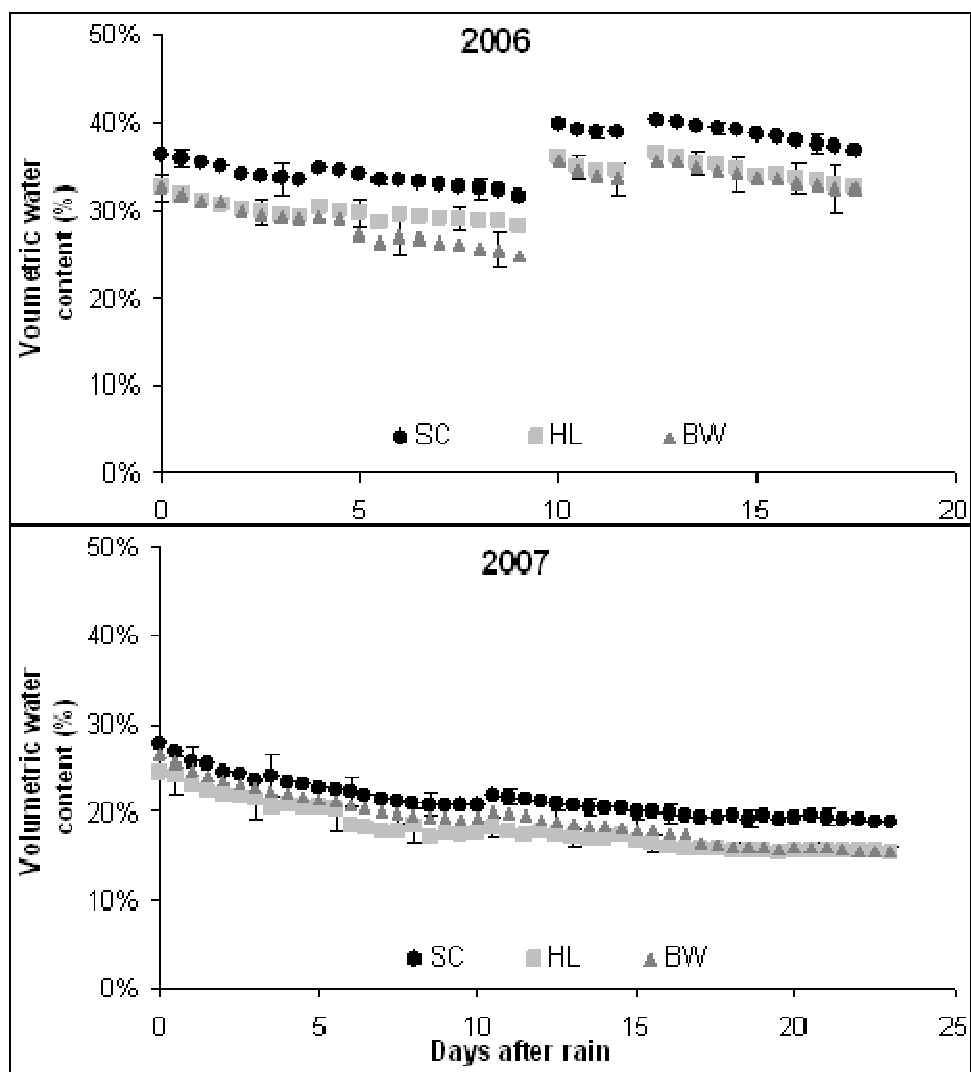


Figure IV.9. Volumetric water content in the top 10 cm of soil separated by treatment in 2006 and 2007, bars represent one standard deviation from the mean. Values are averaged by distance and block.

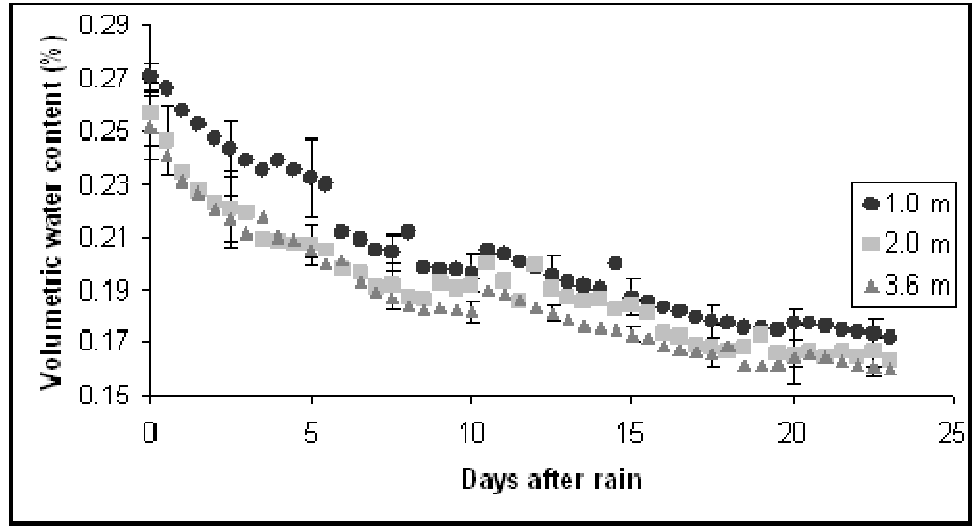


Figure IV.10. Volumetric water content in the top 10 cm of soil separated by distance from the tree, in 2007. Values are averaged across all treatments.

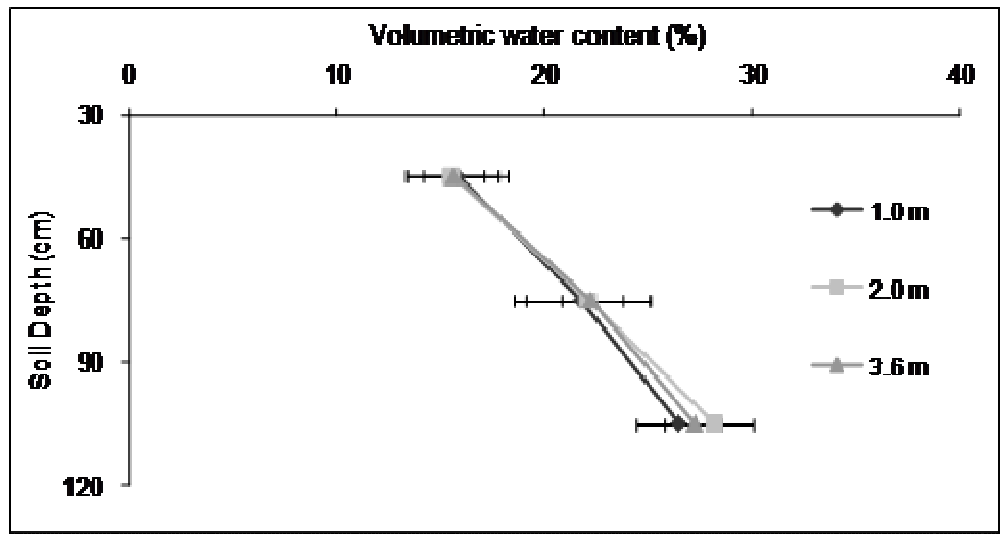


Figure IV.11. Soil volumetric water content by distance from tree and depth. Bars represent one standard deviation. Values are averaged by treatment and block.

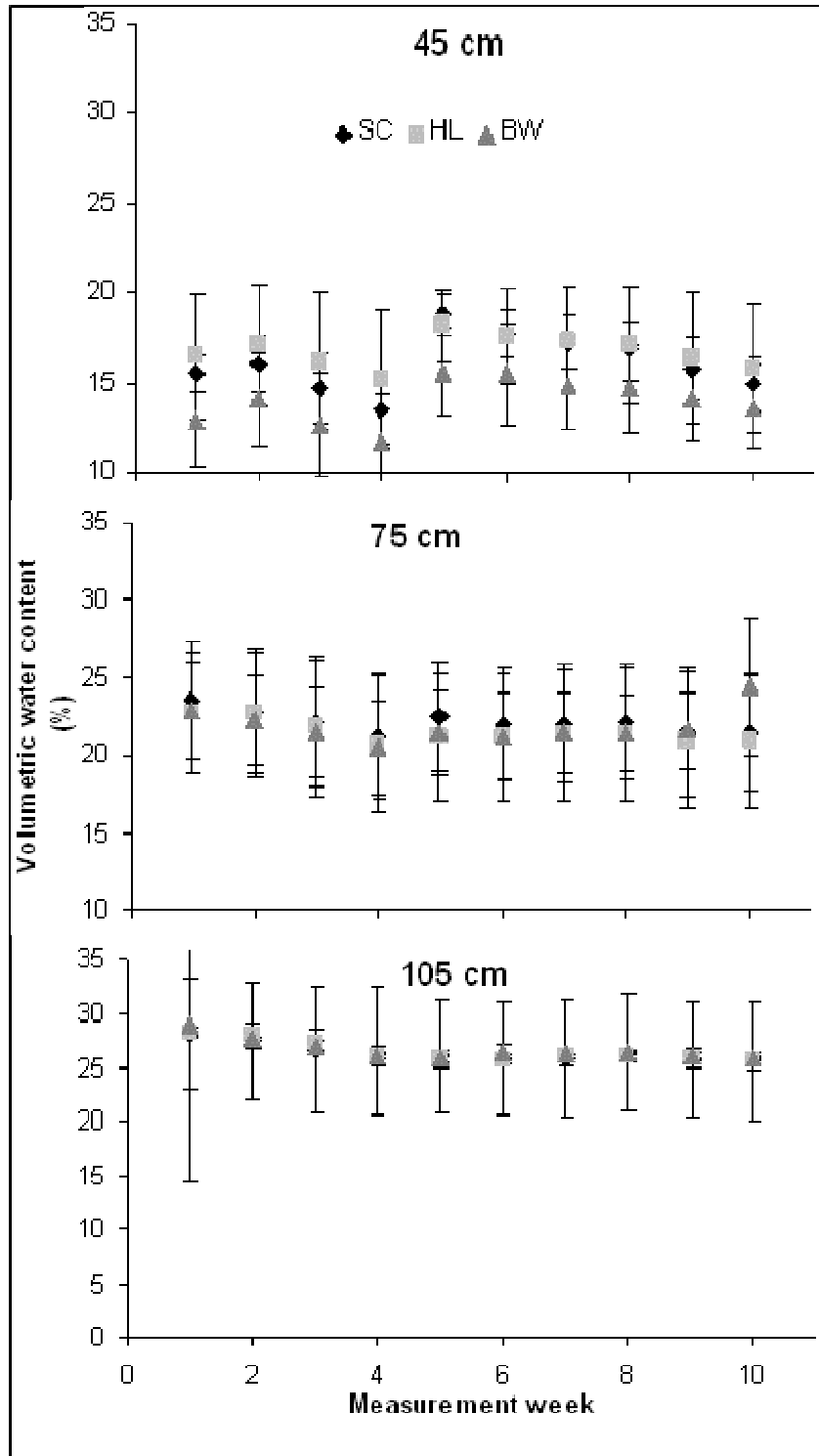


Figure IV.12. 2007 Soil volumetric water content for soils at depths from 45-105 cm by treatment depth and time. Pares represent one standard deviation from the mean. Values are averaged by distance and block.

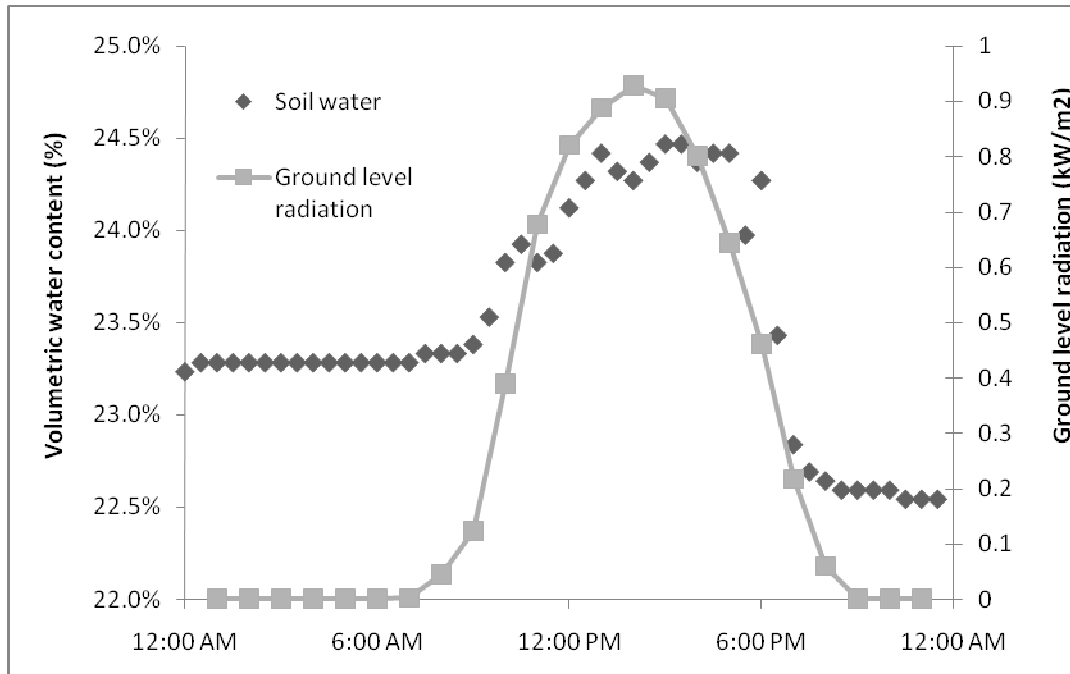


Figure IV.13. Diurnal soil water values from 8/18 2006 for probe located 2 m up-slope from the walnut in block 2. Hash marks indicate 6 hour intervals. There was no rainfall during this period.

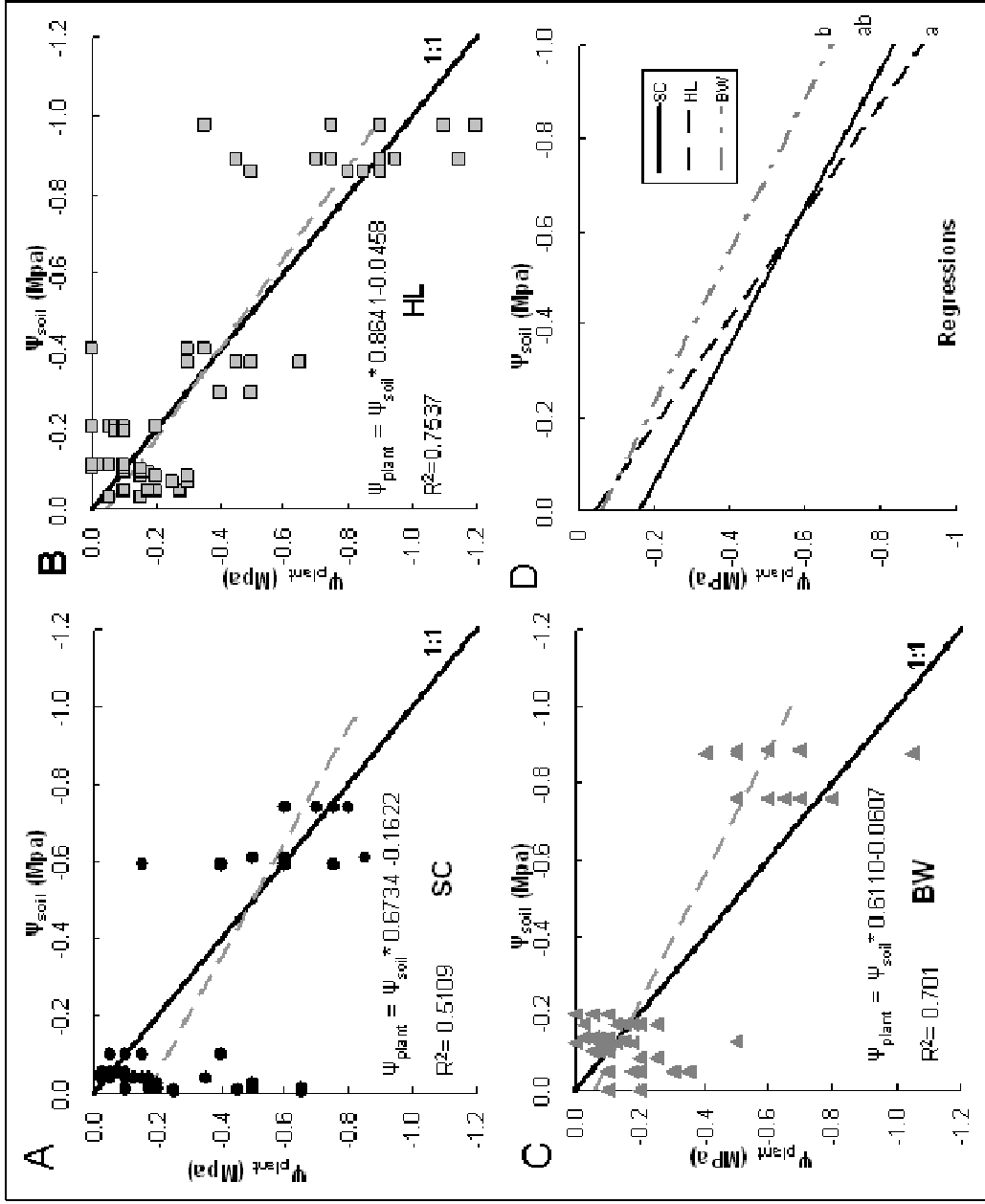


Figure IV.14. Regressions for the Ψ_{soil} to Ψ_{forage} relationship (dashed gray line) under shade cloth (A), honey locust (B), and black walnut (C), the regression lines for all three treatments are shown together for the purpose of comparison (D). The solid black line in A, B, and C is a ratio of 1:1 and has been added for comparison. The equations for the regressions are listed for each treatment as is the R^2 value.

V. Summary

Research in tropical regions has indicated that silvopasture, and other agroforestry practices, can increase forage production and improve soil quality. More recently, there has been research done to determine if the same benefits occur in temperate climates. Temperate silvopastures can also increase forage production and improve soil quality, but the species interactions and underlying mechanisms are still poorly understood.

The goal of our research was to determine the effects of honey locust and black walnut on forage growth, soil water, and soil quality in a central Appalachian silvopasture. There were two studies performed, one on the effects of black walnut (BW) and honey locust (HL) silvopastures on soil quality, the other on the effects of individual BW and HL trees on forage growth and soil water. Soil quality was measured by collecting samples from the top 10 or 15 cm of soil at 1.5 m, 3.0 m and 6.1 m from the tree rows in BW and HL silvopastures and in open pastures (OP). These samples were then tested to for a variety of soil physical, chemical, and biological quality indicators. Forage mass samples and soil water measurements were taken at 1.0 m, 2.0 m, and 3.6 m from the trunk of the tree, or from plot center under shade cloth. Forage samples were collected several times per year to determine total annual yield. Surface soil measurements were taken every half hour from the top 10 cm of soil using capacitance type sensors. Deeper soil water readings were collected from 45 cm, 75 cm, and 105 cm weekly using a neutron probe.

The HL silvopasture had more favorable indicators of soil quality than either the BW silvopasture or the OP. Total C, MoC, total N, and extractable K were significantly higher in the honey locust silvopasture. NH_4 , Ca, Mg, Mn, B, pH, CEC, base saturation

and bulk density showed a numerical trend towards more favorable values in the honey locust, but these values were not statistically significant. Soil indicators including bulk density, base saturation, acidity, Ca, Mn, Mg, and B were also most favorable under tree canopies (1.5 m) and least favorable in the plot center (6.1 m), and K saturation and P had treatment X distance interactions.

Tree species did not affect forage growth. In 2006, forage growth was lower under the 70% shade cloth (SC) than in the tree plots, but growth of unshaded forage in the SC plots was similar to forage growth in the tree plots. In 2007 a 50% SC was used instead of the 70% SC and forage growth was similar in all treatments.

Treatment effects were observed for soil water, but hydraulic lift was not observed. In 2006 initial soil water content in the top 10 cm of soil was lower in the 70% SC plots than in the BW or HL plots. In 2007 soil drying rates in the top 10 cm of soil were higher in BW and HL plots than 50% SC plots. Soil water values from 45-105 cm were similar between treatments. Half-hourly soil water measurements of the surface soil (0-10 cm) did not have patterns consistent with hydraulic lift. Forage water potential vs soil water potential regressions for SC plots were similar to the forage water potential vs soil water potential regressions for BW and HL; this indicated that hydraulic lift was not measured, though it may be occurring on site.

The establishment of silvopastures improved soil quality without degrading forage production. Trends indicate that the silvopasture system was improving the retention of soil nutrients while increasing soil organic matter and reducing bulk density. Distance interactions unassociated with pasture treatments may have been caused by trees scavenging nutrients within the OP plots and accumulating them near the canopy. Forage

growth was similar among all treatments in 2007, and the lower growth under the 70% SC in 2006 was most likely the result of intense shading.

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