Hardwood silvopasture management

H.E. Garrett[1], M.S. Kerley[1], K.P. Ladyman[1], W.D. Walter[1], L.D. Godsey[1], J.W. Van Sambeek[2] and D.K. Brauer[3]

[1]*Center for Agroforestry, University of Missouri, Columbia, MO 65211,* [2]*US Forest Service, North Central Research Station, Columbia, MO 65211, USDA, ARS ,* [3]*Dale Bumpers, Small Family Farm Research Center, Booneville, AR 72927*

Introduction

Land clearing for agricultural purposes began in the Central Hardwood Region with Native Americans and continued under European occupancy. However, despite clearing practices, their was a strong emphasis by an agrarian society to intensively manage woodlands for multiple uses that included not only timber based products, but also livestock grazing, harvesting of edibles and hunting (Koch and Kennedy 1991). As our nation moved from an agrarian to an industrialized society, the use of forests became more singular in purpose, with a strong emphasis placed on producing wood products. However, throughout the 1930's, forest practices, such as high-grading, burning and continuous grazing, were prevalent and continued to impact the overall productivity and quality of the Central Hardwood forests. Though these practices are not as broadly applied today, their influence is still visible in forests whose ages at harvest may be 80 to 120 years.

One of the challenges facing the forestry profession today is how to encourage hardwood landowners to invest in management when financial returns are futuristic at best. Agroforestry provides a means of encouraging good forest stewardship and does so with the outlook of positively influencing productivity and financial gain. In the course of integrating trees and shrubs into farming practices (such as with silvopasture management), multiple objectives are obtainable. In a broad sense, agroforestry is a title encompassing all farm practices that deliberately combine the production of trees and/or shrubs with other crops and/or livestock in a manner that is collectively beneficial. Through the intentional integration of trees with livestock, silvopastoral practices strive to simultaneously optimize economic, environmental and social benefits.

Silvopasture utilizes management practices for growing trees with forage and livestock under artificial agroecosystem conditions. Management schemes incorporate intensive practices. Grazed forests or woodlands extensively managed as “natural ecosystems” similarly produce wood products and forages for livestock or wildlife but without using intensive approaches and with the potential for dire consequences (Bezkorowajnyj et al. 1993, Chandler 1940, Patric and Helvey 1986). These practices are not classified as silvopasture or even agroforestry in general. Silvopasture management, like the other forms of agroforestry, requires shifting our thinking in both spatial and temporal domains, and demands skills in managing, rather than reducing complexity. It challenges land managers to transcend disciplinary boundaries and explore the potential synergism between production agriculture and natural resource management. Essential to this is an understanding of hierarchial scalar relationships within ecosystems and recognition that defined ecosystem “boundaries” exist primarily for managerial convenience (Garrett, et al. 1994, Garrett and Buck 1997).

Potential for hardwood silvopasture

While traditionally trees and forest products have been employed on the farm for a multitude of purposes (timber, fence posts, windbreaks, livestock shelter, etc.), the utilization of farm forests and products has seldom been optimized. The result is a less than optimal use of on-farm resources that fails to maximize the potential benefits.

Hardwood *silvopasture* has great potential. Simply stated, the *silvopasture practice* is developed by integrating trees or shrubs with forages for grazing. Because the practice endeavors to simultaneously produce forest products, high quality forage, and livestock on the same parcel of land, intensive management is required. Silvopasture can be the product of establishing trees in pastures, or grasses and legumes into managed forest stands.

While few data exist that would provide a reliable estimation of the hectares currently under silvopastoral management within the hardwood region, vast areas of forestland, pastureland, rangeland and even cropland that are suitable for the practice are known to exist. The potential for the establishment of silvopasture on highly erodible cropland that would better serve the landowner and society alike if it was planted to trees, is enormous. In the five hardwood states of Missouri, Illinois, Indiana, Iowa and Ohio there are more than 7 million ha of cropland with an erodibility index (EI) greater than 10 (Noweg and Kurtz 1987). Within the Central Hardwood Region (Michigan, Wisconsin, Minnesota, Missouri, Ohio, Indiana, Illinois and Iowa) there is an estimated 34 million ha of forest with 6.6 million occurring on farms. Of the approximately 6.6 million, 2.3 million (35%) is currently being pastured but without the benefit of intensive management (Table 1). The use of forested land for passive grazing varies by regions reflecting diverse views held by landowners. In a survey of four rural Missouri counties conducted by the Missouri Department of Conservation, it was found that 68% of the woodlands were grazed (Hershey 1991). Passive forest grazing is detrimental to the forest and contributes little forage towards sustaining a cowherd. In contrast, silvopasturing of woodlands that are available and currently being mismanaged, has the potential to increase the forested land that is under management for wood production while increasing available pasture area. In the state of Missouri alone, there are 5.7 million ha of timberland of which 10% or less is under management. Missouri has the second highest number of cows of any state in the US. National projections suggest that land area available for grazing is likely to be reduced, due to conversion to other uses, and use of forages for grazing will decrease by 32% (Van Tassell et al. 2001). Silvopasturing would not only increase the pasture area available but could also serve as an incentive for landowners to place currently unmanaged forest land under management.

Table 1. Hectares of forestland and hectares of farm woodland pastured (in millions) by State.[a]

		Farm Woodland [c]		
State	All Forestland [b]	All	Pastured	Not Pastured
		Millions hectares		
Michigan	7.8	0.46	0.06	0.40
Minnesota	6.8	0.81	0.30	0.51
Wisconsin	6.5	1.15	0.29	0.87
Missouri	5.7	1.85	0.92	0.94
Ohio	3.2	0.63	0.14	0.49
Indiana	1.8	0.52	0.11	0.41
Illinois	1.7	0.66	0.17	0.49
Iowa	0.8	0.53	0.26	0.28
Total hectares	34.3	6.61	2.25	4.39

[a] Inventory year 1997

[b] Smith, W.B., J.S. Vissage, D.R. Darr, R.M. Sheffield. 2001. Forest Resources of the United States, 1997. Gen. Tech. Rep. NC-219. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 190 p.

[c] Glickman, Dan.; Gonzalez, Miley; Bay, Donald M. 1999. 1997 Census of agriculture - State data. United States Department of Agriculture: National Agricultural Statistics Service

Progression of Silvopastoral Practices

The objective of employing silvopastoral practices is to integrate the production agriculture components of trees, forage, and grazing herbivores for a production benefit. The benefit supposed is that the tripartite sum is greater than the value of any component individually. The actual benefit realized from implementation of silvopastoral practices is dependent upon understanding the production requirements of each component, and how synergism among the components can be maximized. The potential benefit of silvopastoral practices is not a new concept. Stephenson (1954) noted its written reference in describing the 1783 backwoods of North Carolina. The idea that woodland grazing is inferior is more recent. DenUyl and Day (1934) summarized that forage from farmwoods was inferior in nutritive quality and that grazing farmwoods would negatively impact timber stands due in large part to young tree damage. This is a view that is still widely held in forestry. However, more recent research (Duncan and Reppert 1960, McIlvain and Shoop 1971, Lehmkuhler et al. 2002) has demonstrated that tree, forage, and livestock interactions can be manipulated to enhance forage production and animal growth without negative effects on tree performance. Today, research is focused on understanding the interaction dynamics of the silvopastoral practice. The expected outcome is that silvopastoral practices will be employable that improve the productivity of the grazing animal, the quality and diversity of forage available to the grazing animal and wildlife, and effectively interpose timber stand improvement across a wide array of forested land.

Light availability in woodlots

Site selection (aspect and slope) and the application of management activities (including tree planting, thinnings and logging) can have a dramatic influence on the light available for silvopasture practices. A direct relationship exists on south-facing slopes between degree of slope and percentage of direct solar radiation reaching the forest floor. Gaps up to 2 times the height of adjacent trees on south-facing slopes of 30 degrees have a greater percent direct solar radiation than similar gaps on slopes of 15 degrees (Fischer 1979). Furthermore, an inverse relationship exists between the same slope degrees (15 and 30 percent) and the percentage of direct solar radiation reaching the forest floor on north-facing aspects. The role of gap size has also been quantified in that gaps have little effect on available light when openings are smaller than 0.04 ha and larger than 0.4 ha in size (Dey and MacDonald 2001). Also, most studies of light intensity measured in gaps have emphasized light readings at the center of the gap, recognizing the decreased availability of light when moving from gap center towards the edge (Minckler 1961). For the silvopasture practice and growth of forages, the uneven distribution of light, such as may be created with gaps, is not desirable. But, understanding the role of slope and aspect may play an important role in determining appropriate residual densities when thinning a forest stand. South-facing slopes that naturally receive greater solar exposure should, logically, have higher densities of trees than north-facing slopes that are predisposed to less direct sunlight.

Thinning studies of forested environments to create desirable levels of available light have been conducted. While these studies have primarily been designed in an attempt to create favorable light conditions for regeneration of desirable tree species, the information has direct application to creating light levels favorable for the growth of select forages. Two popular harvesting practices for opening mature forest canopies in hardwood forests and allowing light to penetrate to the forest floor are group selection and the shelterwood methods. The group selection method creates patches of high light intensity, while the shelterwood method is designed to create a more even distribution of light throughout the forested understory. In young immature stands, release thinnings such as timber stand improvement (TSI), crop tree, and deferment cuts, will provide increased light levels for forage production while at the same time improving the growth of trees identified for retention.

Dey and Parker (1996) reported that removing 43 and 77% of the basal area with a shelterwood harvest in an oak stand increased light intensities to 35% and 65%, respectively. Many studies have found that up to 50% of the basal area of hardwood forests may need to be removed to increase light levels to 35-50% of that found in the open (Sander 1979, Marquis 1988, Dey and Parker 1996).

For many plants, full sunlight is not required to maximize growth. Many herbaceous plants need only about 10% of full sunlight to reach a state of growth where photosynthesis exceeds respiration, and will reach light saturation at 50% (C_3 plants) and 85% (C_4 plants) of full sunlight, respectively (Gardner et al. 1985). The light intensity within mature hardwood forests is typically lower than 20% and may be as low as 1% (Dey and MacDonald 2001). While the removal of some proportion of the overstory canopy can increase the intensity and duration of light reaching the forest floor, and thereby improve the growth of forage crops, the relationship of overstory removal to available light is not linear, with an estimated residual stocking density of 30% required to provide light levels of 50% of open values (Sanders 1979).

Potential effects of converting forest stands to silvopasture on tree quality

Forestry practices that reduce stand stocking, such as thinnings to accommodate silvopastoral management, can have both positive and negative effects on the residual trees. The quality of any tree is measured by its ability to meet the specifications/expectations that are defined by the product of end-use. Tree utilization is broad and may include products such as nuts and lumber, or services provided to society, such as filtering water (riparian buffer strips) and air (CO2 sequestration). Tree species will vary in their ability to provide related end-products. However, maintaining the health (growth and productivity) of individual trees is paramount to their utility. Any injury or inhibition of growth resulting from management (thinning, grazing, etc.) is undesirable.

Thinning or release of hardwood stands, especially young stands, normally benefits growth. In general, tree growth (especially diameter) has been shown to increase as stand density decreases (Dale 1968, Dale and Sonderman 1984, Schlesinger 1978). Even older stands may show strong growth responses following a thinning. A study by Smith and Miller (1991) reported significant improvements in growth rates of released 75- to 80-year-old Appalachian hardwoods. Additionally, Dale (1975) observed improved growth of older overstory trees with the removal of the understory.

Stokes et al. (1995) identified a general trend of an increasing number of damaged residual trees per ha with a decreasing number of trees removed. Further, while the operations of a silvopasture practice might benefit from whole tree removal, the process of whole tree removal can result in significant damage to residual crop trees. In thinnings of hardwood stands, up to a third of the residual stand may be damaged (Ostrofsky et al. 1986). In most studies, a significant portion of the damage to residual trees has been linked with skidder activities and could have been avoided through better planning of logging activities (Reisinger and Pope 1991, Ostrofsky et al. 1986). These wounds, while ultimately resulting in defect, may also become points of entry for pathogens which result in wood rot and/or tree death. Both decay and discoloration begin with the creation of a wound, and can ultimately lead to decreased value of residual timber (Shigo 1966, Shigo 1979). This is highly undesirable as it is one of the goals in silvopasture management to maximize the financial returns.

Another effect of thinning, which especially must be considered in establishing a silvopasture program, is the development of epicormic branching. Many factors (age of the tree, crown position, vigor, evidence of previous sprouts, site aspect and species) may be indicators of the potential for epicormic sprouting. Smith (1966) ranked several common hardwood species relative to their potential to develop epicormic branches. White oak (*Quercus alba* L.) had the highest likelihood followed by a grouping of black cherry (*Prunus serotina* Ehrh.), red oak (*Q. rubra* L.) and chestnut oak (*Q. prinus* L.). A grouping of hickory (*Carya* spp.), yellow poplar (*Liriodendron tulipifera* L.), red maple (*Acer rubrum* L.) and sugar maple (*Acer saccharum* Marsh.) ranked third. White ash (*Fraxinus Americana* L.) showed the least likelihood. Trees are less likely to develop epicormic branching when they are vigorous dominants or co-dominants and have shown no previous evidence of epicormics (Lamson et al. 1990, Ward 1966). Brinkman (1955) noted that epicormic scars may result in lower log values. Thinnings designed to reduce stand density to 40 to 50 percent, (similar to the requirement in silvopasture management) while leaving vigorous co-dominant crop trees that show no evidence of epicormic sprouts, has been shown to minimize epicormic development (Lamson et al. 1990).

Regeneration and sustainability of a silvopasture woodland

One of the criticisms of allowing livestock access to farm woodlands relates to their potential negative impact on forest reproduction and thus sustainability. When nutritional forage is available, most livestock, especially cattle, will not seek out the less palatable woody browse (Hall et al. 1992, Hawley and Stickel 1948). However, any browsing of terminal shoots by domestic or wild animals will result in deformity and loss of growth (Den Uyl et al. 1938). All silvopasture programs must be sustainable to be successful, whether trees are established in pastures or forages in woodlands. Sustainability implies that some form of regeneration is planned for. Due to the inherent characteristics of hardwood silvopasture, artificial regeneration is required along with physical protection. Lehmkuhler et al. (2002) demonstrated the benefits of a single strand of high tensile electric-charged wire positioned along both sides of a row of trees in protecting them from livestock. A solar panel attached to batteries made the system cost effective. However, some landowners prefer a simpler means of protection. For these individuals, wire cages or tree shelters might better serve their needs. Tree shelters (i.e., tubes within which seedlings begin growth) are becoming more popular but are expensive (Lantagne 1991, McCreary and Tecklin 2001, Minter et al. 1992). Individual wire cages are likewise expensive but have the advantage of being readily adaptable to protecting, not only from browse but also from hoof damage, scattered "strategically positioned" seedlings whether planted in an understory or open pasture. Hardwood silvopasture studies underway at the University of Missouri, Center for Agroforestry utilize containerized oak seedlings protected by wire cages. In these studies, pole-size white oak stands have been thinned to approximate 50% crown cover. RPM-produced white oak seedlings are strategically positioned in the understory in sufficient numbers per ha to represent the next generation stand. The RPM containerized seedlings which range in height from 1.2 to 2.0 m with a large root mass at time of planting, show remarkably fast juvenile growth and can be producing mast at age 3 (Lovelace 1998, Dey et al. 2003). The wire cages provide excellent protection and the RPM seedlings provide assurance that the practice will be sustainable.

Grazing Livestock

Cattle and sheep are the primary species of domesticated livestock used in silvopastoral practices. The primary difference between silvopastoral and open canopy management of these species is the contrasting environmental conditions. In the open, such as a conventional pasture or range, radiant heat can be much more intense than in a shaded environment. Shade has been shown to improve animal performance, with primary emphasis placed upon heat stress amelioration. McDaniel and Roark (1956) conducted a shade experiment with Angus (black hair coat) and Hereford (red and white hair coat) cows comparing artificial or natural shade to open pastures. The natural shade consisted of abundant, savannah-type tree spacing, and scanty shade, clusters of trees in the grazed pasture, treatments. Cows of both hair coat colors gained more than cows without shade, as did their calves. During the daylight hours from 6 am to 7 pm, the cows on the abundant shade treatment spent the most time grazing, with grazing time decreasing concomitantly with decreasing shade. McIlvan and Shoop (1971) measured improved gains in yearling Hereford steers on rangeland given access to shade. Of particular interest in their findings was that shade could be used to create more uniform, or less spot grazing by cattle. Shade was noted to be nearly as effective as water placement or supplemental feeding location to promote uniform grazing within a pasture. Silvopastoral practices could be extrapolated to encourage more uniform grazing and waste nutrient deposits within a pasture compared to open pasture or range. The natural shade areas, particularly the abundant shade treatment, resulted in superior weight gain of cattle compared to the artificial shade treatment. Planted or natural trees are usually an effective source of shade and potentially superior to manufactured shade structures because their radiosity is lower than flat-roofed structures, giving them a larger low temperature ground area with good exposure to the north (Kelly et al. 1950).

Heat and cold stress can adversely affect cattle throughout much of the temperate zone in North America. Protection from cold can be especially important for livestock in northern climates. Properly positioned trees and shrubs or natural forest stands can provide much-needed protection for pastures, feedlots and calving areas. Reducing wind speed lowers animal stress, improves animal health and increases feeding efficiency of livestock. Canadian researchers have demonstrated that cattle on winter range require an additional 20% increase in feed energy, above maintenance, to offset the direct effects of exposure to a combination of cold temperatures and wind. Adequate wind protection has been found to reduce the direct effects of cold by more than half (Webster 1970). Similar findings have been reported for swine and dairy animals (Hintz 1983).

However, Worstell and Brody (1953) noted that greater emphasis should be placed on prevention of heat stress than cold stress in cattle. When an animal is subjected to an environment that causes heat stress, the behavior of the animal adjusts to alleviate the heat stress. The symptoms of heat stress begin to occur at 30 C (Cartwright 1955). Two such behaviors are reduced intake, to lessen metabolic heat production, and seeking relief from the heat source, such as standing in water or under shade. In a study on the effects of heat on dairy animal milk production, University of Missouri animal science researchers found that increasing temperatures from 20 to 29°C resulted in daily milk production decreasing from 39 kg to 26 kg and feed intake per cow decreasing from 38 to 32 kg (personal communication, Jim Spain, University of Missouri). Similar findings have been reported by others (Spain et al. 1997, Muller et al. 1994). Alleviating heat stress by providing a shaded environment would potentially increase intake, which would increase animal growth. An animal in its thermoneutral zone would also be more likely to graze during daylight, increasing its ability to select high quality forage, and therefore a more nutrient dense diet. However, our understanding of the dynamics between shade and animal behavior is very limited. More research is needed to elucidate how shade and tree canopy structure influence animal behavior under heat and cold-stressed environments.

Forage Production

Forage production and nutrient content are the two variables that will determine the productivity of the grazing animal, and thus the productivity of the grazing system. The mass of forage available is obviously important to sustain animal growth; the general idea being that the more forage available for grazing will either increase the number of animals that can graze per unit of land or support a longer grazing time. The nutrient content and/or digestibility of the forage will determine the rate of growth or performance. The fiber content of the forage is negatively correlated to forage intake and digestibility. As forage intake increases, animal performance would obviously increase. The greater the digestibility, the greater the digestible energy content of the forage. Forage digestibility is controlled by the fiber content of the grazed plants and the chemical structure of the fiber. Typically, as fiber content increases forage digestibility will decrease. However, this correlate exists because as forages increase in proportion of fiber they concomitantly increase in the proportion of secondary cell wall. The secondary cell wall, due to lignification, is reduced in susceptibility of cellulose and hemicellulose to hydrolysis by the bacterial cellulase complexes in the animal's gut. Protein content of the forage is also important to nutritional quality of the forage. As the forage protein content increases, more nitrogen and peptides are available to the rumen microflora, which can stimulate their growth, and more protein is available to the animal. The goal in producing forage for grazing or hay production is to increase the forage protein content and digestibility.

Forage management practices have been identified that improve the carrying capacity or stocking density of pastures. In addition to the provision of nutrients via soil fertilization, grazing management programs have been employed to enhance plant growth and survival. These programs encompass allowing access to pastures for specified time periods and then removing the animals to allow the plants rest from grazing pressure (i.e., rotational grazing). The goal being that the more nutritious plants, preferentially selected by the grazing animal, are not overgrazed and thus limited in their production or lost from the pasture or range. The primary benefit from managed grazing programs is that forage production is increased, which allows greater animal stocking densities per unit of land and the potential for greater profitability. Forages grown in a silvopastoral practice need to be evaluated for the effect of canopy on forage production and nutrient quantity and the effect of grazing management programs on forage productivity under shade.

The general conclusion is that forage yield in a silvopastoral practice is decreased with increased tree basal area (Wolters, 1973). Pearson (1990) noted that forage yields generally decrease as tree overstory increases. However, he also noted that integrating timber and grazing management can result in greater profit than from either enterprise alone – a conclusion also reached by the Spanish inhabiting Florida in the 1600s. The approximate 40 million ha of forestland in the southeast alone (Shiflet 1980) makes the potential for silvopastoral practices great and important. Moreover, millions of hectares of hardwoods are available that could also be placed under management using silvopasture technology. Therefore, the question that arises is, can forage species and tree-forage interactions be identified that have a positive influence on forage productivity?

Ehrenreich and Crosby (1960) determined that forage production increases when hardwood tree-crown cover is reduced below 50%. They also measured only small per unit reductions in grass production as crown cover increased from 50 to 80%. Their research further noted that forage species under dense canopies differed from species under less dense canopies or in the open. As this research pointed out, forage species differ in their adaptability to shade stress. Holechek et al. (1981) showed that forage nutrient composition was altered by a shaded environment, similar to results found by Roberts (1926). Forage grown under a forest canopy had higher crude protein and greater in vitro organic matter digestibility than when grown in the open. Interestingly, they also found that digestibility was influenced by shade and season, with digestibility being greatest for grass grown under shade in the summer and greatest for grass grown in the open in the fall when adequate rainfall occurred. They also noted that forage species under the forest canopy were more diverse than in an open area. They suggested that the most efficacious grazing system would combine grazing under a forest canopy with open pastures at different points in time during the grazing season. Frost and McDougald (1989) reported that herbaceous production was 115 to 200% greater under scattered oak than on open grassland. They attributed the response to more favorable physical and chemical soil properties and a more favorable soil temperature. Demonstrating the importance of tree-forage interactions, they measured differences in forage production under canopies of blue oak, (*Quercus douglasii* Hook and Arn), interior live oak (*Quercus wislizenil* A.D.C.) and digger pine (*Pinus sabiniana* Dougl.). They concluded that the increased forage production was in large part due to shading in drought conditions reducing moisture loss via evapotranspiration. Standiford and Howitt (1993) further defined the link between forage production under varying canopy and rainfall conditions and concluded that areas receiving less than 50 cm of rainfall will result in greater forage production under shade than in the open, with just the reverse result in areas receiving more than 50 cm of rainfall. Kay (1987) showed greater forage production in the open than under dense oak canopy woodlands with rainfall of 50 to 75 cm. Standiford and Howitt (1993) developed models in an attempt to quantify the various influences on forage production under canopy. They concluded that forage production was influenced by crown cover, rainfall, the interaction of rainfall and crown cover, and growing-degree days. Based upon their model, canopy had the greatest effect in depressing forage yield in higher rainfall areas.

Our assessment is that the productivity of forage in a silvopastoral practice in the temperate zone of North America is dependent upon tree and forage species in addition to canopy structure and climatic conditions (rainfall amount and seasonality). As noted by Clason and Sharrow (2000), the relationship between the overstory trees and the understory forage species must be compatible. Warm and cool season grasses respond differently to shade stress. Increased temperature increases cell wall content of cool-season grasses (Ford et al. 1979). Grasses respond to shade stress by increasing leaf-area and shoot-to-root ratio (Allard et al. 1991, Kephart et al. 1992) and by concentrating nitrogenous compounds (Kephart and Buxton 1993). Huck et al. (2001) evaluated several grass species under shade stress in Missouri and found that cool-season grass production was often increased under 45% sunlight compared to full sunlight, and that nitrogen and fiber digestibility was also improved in forages grown under shade. Interestingly, they also found that fiber concentration of the grasses was increased. These findings agreed with Garrett and Kurtz (1983) who measured higher in vitro digestibility of fescue (*Festuca arundinacea* Schreb.) and orchardgrass (*Dactylis glomerata* L.) grown under a walnut (*Juglans nigra* L.) canopy than when grown in open pastures. Lin et al. (1999, 2001) have recently identified several cool-season grasses and legumes for the midwest that perform better at 50% shade than in full sun. Not only were significant increases in yields observed, but the quality of the forage was also found to be superior in the shade. This more recent research has demonstrated that forage species can be selected that thrive under reduced sunlight conditions, even producing greater masses of dry matter with superior nutritional quality than when grown in full sunlight. By understanding how the physiology of different forage species responds to shade stress, hardwood silvopastoral practices can be more effectively designed to enhance grazing animal performance.

Integrating trees, forages, and animals

The three items in a silvopastoral practice that can be subjected to management are tree species, tree density, forage species, and animal maintenance. The majority of research conducted has evaluated silvopastoral practices under conifers (mostly pine) with limited work in hardwoods. Most hardwood research has been conducted with either oak species or nut-bearing species (e.g., black walnut). Pine canopies will tend to reduce forage growth in the immediate area where pine needles fall on the floor, owing to the mulching capability of pine straw. There is also a strong correlation between light intensity and forage production under pine canopies as there is in hardwoods. However, forage production between pine tree rows has been found to be as good as that in open areas and the potential for successful silvopastoral practices in pine stands has been demonstrated. In deciduous tree stands, forage production has often been reported to be equal or greater under canopies than in open exposure to sunlight. Fescue and orchardgrass production was greater under a 35-year-old walnut canopy than in open pastures (Garrett and Kurtz 1983). Forage production was found to be two-fold greater following walnut establishment into existing pastures than it was without trees (Smith 1942, Neel 1939). Spatial arrangement and management of trees can be designed such that tree damage from livestock is negligible. The two most important factors in preventing tree damage appear to be that crown height of the tree is above grazing height and that the tree is large enough to prevent damage by rubbing and trampling. New or young plantings must be protected by electric fencing or by other means because tree species that are susceptible to predation from the grazing animal will sustain damage (Lehmkuhler et al. 2003). Older trees must be protected from soil compaction and physical damage to roots near the surface through the use of rotational grazing and livestock removal during wet periods. The general consensus of the reported literature is that tree performance is not altered in a silvopastoral practice once the tree is of sufficient size to prevent physical damage of the stem or browsing of the crown assuming proper management recommendations are followed (i.e., rotational grazing, etc.).

The production and quality of forage produced in a silvopastoral practice will be influenced by forage species present. Typically, maximizing forage production will require that cool season grass and legume species be selected that are adaptable to shade stress. It is possible to use forage species that will increase the dry matter produced and nutritional quality of forage superior to what would be produced in an open pasture. These forage species are well adapted and indigenous to the temperate zone of North America (Lin et al. 1999, 2001). Managed grazing practices, similar to open pastures, should be developed and implemented to maximize forage production in a silvopastoral practice. The increased forage production under a canopy would result in increased stocking rate potential and greater productivity per unit of land.

Animal performance can be enhanced via use of silvopastoral practices. This occurs from reduction of heat stress and improved forage availability and nutritional quality. Increased performance potential can be achieved without negative effects on tree growth if proper management practices are adopted. Stocking density should be designed to prevent over grazing of the forage production potential and damage to residual trees.

Economics of silvopasture

Economics is the study of “choice”. Faced with a limited amount of resources, resource managers must make choices regarding use. From a supply and demand perspective, natural resources must be managed in such a way that maximum needs are met with a finite supply of resources. Benefits to good resource managers can be tangible, such as monetary rewards, or intangible, such as aesthetics or self satisfaction. However, regardless of the benefit to the resource manager, each benefit is the result of a choice, or trade-off that is made. The trade-off often revolves around three main objectives: financial benefits, environmental benefits, and social benefits. From a silvopastoral perspective, a landowner must balance the use of land, animal and labor resources in a way that provides the greatest net benefit to him/her and society.

Ranchers who choose to graze their cattle on open pastures have made a choice to forego the cost of establishing trees in their pastures (a financial benefit of decreasing pasture cost) while also foregoing the benefits of reducing heat stress on the animals, improving forage quality, sequestering carbon, perhaps mitigating nutrient-rich runoff, and the futuristic prospect of income from the trees. Although financial benefits can be derived in the future from current intangible benefits, decisions are often driven by immediate, measurable financial benefits.

Financial benefits of silvopasture

A rational decision maker will not choose to adopt a land-use practice where costs outweigh benefits. However, because of difficulties in measuring all benefits, resource managers often choose to adopt a land-use practice that only maximizes financial benefits in response to financial costs. As a result, the land-use practice adopted may not be the best practice. Benefits to the resource manager, society, and the environment may be lost due to lack of knowledge of all benefits and asymmetric decision information.

Although financial indicators may not reflect all benefits that could be attained through the adoption of a silvopasture practice, they do reflect benefits that are valued by the resource manager. Understand that "value", "price" and "cost" are not synonymous terms. However, the terms "benefit" and "value" are very similar. The distinction between "value" and "price", or "value" and "cost" is important when analyzing any natural resource practice. "Price" is a quantitative indicator of the interaction of market forces. "Value," on the other hand, is a qualitative assessment of benefit, or utility. Financial indicators must be able to accurately reflect value while using monetary terms such as price.

Common financial indicators applied to silvopastoral practices include net present value (NPV), internal rate of return (IRR), annual equivalent value (AEV), or land expectation value (LEV) (Kurtz et al. 1996, Hubbard et al. 1998, Godsey 2000). These indicators measure the financial costs and benefits of silvopastoral practices for long-term, intermediate-term, or short-term analysis purposes. Although these indicators can be used for comparison purposes, resource managers understand that cash flow is the key to their sustainability.

Most financial analyses of silvopastoral practices come out of the southern pine area of the United States. Grado et al. (1998, 2001) focused on LEV to measure the success of silvopasture in Mississippi where they combined livestock with loblolly pine (*Pinus taeda L.*) and fee hunting. Six alternative land use treatments were analyzed over a period of eight years. Treatments consisted of loblolly pine only, loblolly mixed with livestock, and livestock only. Results showed that LEV's for the silvopastoral practices were more than double that of pine only. The livestock only treatments yielded LEV's twice that of the silvopasture practices. However, in the process of determining LEV's, total costs and returns per hectare were calculated and average annual net income was derived. These indicators showed that both of the silvopasture treatments and only one of the livestock treatments had positive average annual net incomes per hectare.

Lundgren et al. (1983) calculated the real rate of return for four silvopasture practices with three rotation lengths (30, 40, and 60 years) and varying intensities of thinning (no thin, 1 thinning, 2 thinnings, and 4 thinnings). Their results showed that silvopasture managed under the described conditions had a very satisfactory real rate of return ranging from 0.5% to 4.5%. Husak and Grado (2001) built on these two studies to compare the economic performance of silvopasture with that of soybeans (*Glycine max* (L.) Merr.), rice (*Oryza sativa* L.), cattle, and a pine plantation. Using LEV, equivalent annual income[1] (EAI), and rate of return (ROR) as the primary indicators for comparison, silvopasture practices were shown to outperform the other four land use practices in all cases. This study found that silvopasture had an ROR of 14.6%, whereas cattle systems had an ROR of 12.9% and pine plantation systems an ROR of 13.4%. Husak and Grado (2001) further applied income from hunting leases ranging from \$7.41 ha^{-1} to \$19.76 ha^{-1} to the silvopasture system, showing that the hunting revenue could further increase the financial performance of silvopasture by between 5.1% and 26.4%, respectively.

Numerous other financial studies of silvopasture are available from the southern US, yet the conclusions are the same. Silvopasture has been found to improve financial performance over pure forestry or pure livestock management practices. This financial benefit is measured by increased NPV (Husak and Grado 2001, Harwell and Dangerfield 1990), increased annual equivalents (whether it be annual equivalent income or land equivalent values) (Husak and Grado 2001, Grado et al. 2001), improved cash flow (Harwell and Dangerfield 1990), or higher rates of return (Lundgren et al. 1983, Harwell and Dangerfield 1990). Clason (1999) even showed that future net value (FNV) can be improved by adopting a silvopastoral practice with loblolly pine.

Few financial analyses of silvopasture in hardwood stands have been reported. Although there are silvopasture practices that incorporate cattle with mixed pine and hardwoods or just hardwoods in the southern United States, very little has been written regarding the economics of those practices (Zinkhan and Mercer 1997). Standiford and Howitt (1993) modeled resource dynamics and interrelationships by looking at the effects of "multiple use management" (silvopasture) on firewood production, livestock production, and commercial hunting. Their study showed that managing for livestock, firewood and commercial hunting nearly doubled the expected net present value (NPV) over managing for livestock alone. The potential for silvopasture in hardwood stands is relatively untapped. For states like Missouri, where oak-hickory forests are predominant, a silvopasture practice could provide a profitable means of inspiring landowners to manage underutilized forestland.

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[1] Equivalent annual income (EAI) is essentially the same concept as equivalent annual value (EAV).

Currently, a study is being conducted by the University of Missouri, Center for Agroforestry that is designed to evaluate the economics of establishing a silvopasture practice in an existing pole-size white oak stand. The study will measure the financial implications of establishing silvopasture in existing stands versus establishing trees in existing pastures or grazing open pastures. Preliminary analyses indicate that although some income is generated from the initial commercial thinning (woodlot), that income may not be enough to offset the cost of establishing the forage component. Obviously, placing older stands (larger diameter trees) under similar management could yield a greater initial income. However, imposing a silvopasture practice on a previously unmanaged timber stand shortens the rotation of the timber income, creates faster tree growth and larger trees of greater value, and increases grazing land for cattle, thus improving the overall profitability of the land base.

Environmental and social benefits

Financial benefits are only one of many resulting from sound resource management. Zinkhan and Mercer (1997) noted that along with financial benefits (increasing economic returns, diversifying outputs and income, and shortening the wait for income), silvopasture practices also provide conservation and environmental benefits.

Although enhanced wildlife habitat is considered in many of the financial studies (Grado et al. 2001, Husak and Grado 2001), the value of that benefit is often measured only by hedonic pricing methods that look at revenue generated from hunting leases. However, there are also intangible benefits associated with improving wildlife habitat that are more difficult to measure.

Other benefits from silvopasture that are noted in the literature include the intangible benefits resulting from the synergies of tree – livestock interactions. More specifically, the use of manure as fertilizer for the trees and the climate-stabilizing effects of the trees on the livestock which reduces animal stress (Zinkhan and Mercer 1997, Muller et al. 1994, Spain et al. 1997). Water and air quality can also be significantly impacted as a result of hardwood silvopasture adoption. Agriculture-derived contaminants such as sediment, nutrients, and pesticides, constitute the largest diffuse source of water-quality degradation in the United States. Surface runoff and subsurface flow from pasture sites can cause significant nutrient loading of water sources. Excessive pollutants have deleterious ecological impacts on the receiving waters of streams and lakes. Employment of catchment strategies such as silvopasture management can help reduce pollutants before they enter aquatic systems.

Research has demonstrated that inclusion of trees within agricultural systems can improve water quality (Lowrance 1992). Nutrient uptake and removal by the soil and vegetation in a wooded ecosystem (either through tree plantings in pastures or grazing cattle in wooded settings) has been shown to prevent agricultural upland outputs from reaching stream channels. Forested areas function as bioassimilative transformers, changing the chemical composition of compounds. Under oxygenated soil conditions, resident bacteria and fungi mineralize runoff-derived nitrogen which is then available for uptake by soil bacteria and plants. Livestock-created nutrients moving to streams and ground water are reduced due to absorption by roots. Greater infiltration of nutrient-transporting water occurs within forested areas than in cultivated soil. Processes involved include retention of sediment-bound nutrients in surface runoff, uptake of soluble nutrients by vegetation and microbes, and absorption of soluble nutrients by organic and inorganic soil particles (Garrett et al. 1994).

Global warming results from the buildup of trace gasses in the atmosphere. Projections for increases in global surface temperatures range from 5º to 15ºC. A major contributing factor is the dramatic increase in ambient carbon dioxide levels. Tree planting in pastures or enhancement of the vigor of woodlots through thinning and incorporating silvopasture management, presents many opportunities to sequester atmospheric carbon dioxide and mitigate the impacts of global warming. Fast-growing trees take up carbon at high rates. Trees, as long-lived perennials, are an effective storage system for sequestered carbon and carbon dioxide (Henderson and Dixon 1993). Studies have demonstrated that an "average tree" sequesters about 6 kg of carbon and carbon dioxide per year. If in agroforesry, trees were planted using a 3 by 12 m spacing, a spacing that could be used in establishing trees in a pasture, these 267 trees per ha could potentially tie up 1575 kg of CO_2 ha^{-1} $year^{-1}$ (Garrett et al. 1994).

Landowners should not overlook the potential financial value of silvopasture sites for carbon sequestration (Nair and Nair 2002). Silvopasture and all other agroforestry practices have the potential to generate income from carbon credits, with a global market for sequestering carbon ranging from \$2.45 to \$18.00 $tonne^{-1}$ of sequestered carbon (Parcell 2000). Based upon a potential sequestration of 1,550 kg $ha^{1}yr^{-1}$, this could mean additional income for the landowner of \$4.68 to \$34.60 $ha^{-1}yr^{-1}$. Clason and Sharrow (2000) also note intangible social benefits, such as aesthetics, social responsibility (being a good neighbor), and intergenerational responsibility (stewardship for future generations) that help determine the success of a silvopasture practice. A study in Missouri in 1998 (Raedeke et al. 2003) also found that intergenerational equity was the most important reason for planting trees in an agricultural landscape followed by erosion control and wind protection.

Future research

The historical recording of grazing under trees dates to the late 1600's. Initially, grazing animals were subjected to silvopastoral-type practices due to lack of management and fencing. Research then led to the conclusion that grazing under trees should be averted due to poor forage production and animal growth and damage to trees and understory. Now, current research is demonstrating that managed grazing under tree canopies, or true silvopastoral practices, can benefit a grazing animal enterprise. Implementation of silvopastoral practices should be considered in open pastures for two reasons, to increase animal productivity and to generate additional value in timber and/or nut production. Silvopastoral practices should be considered in unimproved hardwood timber for two reasons as well, to improve animal productivity and to implement timber stand improvement practices and place millions of hectares of unmanaged forests under management. The optimum solution will most plausibly be a combination of open pastures and silvopastoral practices integrated into an animal production system.

Research is needed to fully develop silvopastoral practices permitting them to be incorporated into existing grazing systems. A better understanding of how silvopastoral practices can be combined with conventional grazing is needed. We need to better understand the ecological interplay between forage and tree species subjected to silvopastoral practices. We need to develop predictive models that allow us to gauge how grazing stress applied to the forage affects tree growth and productivity over time on a variety of soil types. Specifically, we need to determine how wood quality and/or nut production are affected in a silvopastoral practice. We also need to develop methods of establishing new plantings and ensuring the regeneration of tree species in land subjected to silvopastoral practices. Silvopasture can provide significant benefits to agriculture, wildlife, and the environment. Consequently, it is imperative that research determine how these benefits can be maximized. Thus, we are not repeating history by cycling back to the practice of silvopasture, rather we are correcting the error in our ways of ever ceasing its practice.

References

Allard, G., C.J. Nelson, and S.G. Pallardy. 1991. Shade effects on growth of tall fescue: I. Leaf anatomy and dry matter partitioning. Crop Sci. 31:163-167.

Bezkorowajnyj, P.G., A.M. Gordon, and R.A. McBride. 1993. The effect of cattle foot traffic on soil compaction in a silvopastoral system. Agroforestry Systems 21: 1-10.

Brinkman, Kenneth A. 1955. Epicormic branching on oaks in sprout stands. Technical Paper 146. Research Paper, NE-47. Columbus, Ohio: U.S. Department of Agriculture, Forest Service. 8 p.

Cartwright, T.C. 1955. Responses of beef cattle to high ambient temperatures. J. Anim. Sci. 14:350-362.

Chandler, Robert F. Jr. 1940. The influence of grazing upon certain soil and climatic conditions in farm woodlands. J. Amer. Society of Agronomy 32(3): 216-230.

Clason T.R. 1999. Silvopastoral practices sustain timber and forage production in commercial loblolly pine plantations of northwest Louisiana, USA. Agroforestry Systems 44(3), 293-303.

Clason T.R. and S.H. Sharrow. 2000. Silvopastoral practices. In: (H.E. Garrett, W.J. Rietveld, R.F. Fisher, ed's) North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy: Madison, WI. 119-147.

Dale, M.E. 1975. Effect of removing understory on growth of upland oak. Research Paper, NE-321. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 10 p.
Dale, Martin E. 1968. Growth response from thinning young even-aged white oak stands. Research Paper NE-112. Upper Darby, PA: USDA, Forest Service, Northeastern Forest Experiment Station. 19 p.
Dale, M.E. and D.L Sonderman. 1984. Effect of thinning on growth and potential quality of young white oak crop trees. USDA Forest service Research Paper NE-539.
DenUyl, D., and R.K. Day. 1934. Woodland carrying capacities and grazing injury studies. Purdue University Agr. Exp. Sta. Bulletin 391.
DenUyl, D., O.D. Diller, and R.K. Day. 1938. The development of natural reproduction in previously grazed farm woods. Purdue Univ. Agr. Exp. Sta. Bul. 431.
Dey, D.C., J. Kabrick, J. Grabner, M. Gold. 2003. Restoring oaks in the Missouri River floodplain. In: Proceedings 29th Annual Hardwood Sym. Hardwood silviculture and sustainability: 2001 and beyond. May 17-19, 2001. French Lick, IN. National Hardwood Lumber Association. Memphis, TN. pp. 8-20.
Dey, Daniel C., G. Blake MacDonald. 2001. Overstory Manipulation. In: (R.G. Wagner and S.J. Colombo ed's); Regenerating the Canadian Forest: Principles and Practice for Ontario. Markham, Ontario, Canada; Fitzhenry & Whiteside Limited. pp. 157-175.
Dey, Daniel C. and W.C. Parker. 1996. Regeneration of red oak using shelterwood systems: ecophysiology, silviculture and management recommendations. Ont. Min. Nat. Resour., Ont. For. Res. Inst. For. Res. Inf. Pap. 126. 59p.
Duncan, D.A., and J.N. Reppert. 1960. A record drought in the foothills. USDA Forest Serv., Pacific Southw. Forest and Range Exp. Sta. Misc. Paper 46.
Ehrenreich, J.H., and J.S. Crosby. 1960. Herbage production is related to hardwood crown cover. J. Forestry. 56:564-565.
Fischer, B.C. 1979. Managing light in the selection method. In: Proceedings Regenerating Oaks in Upland Hardwood Forests, The 1979 J.S. Wright For. Conf. (Purdue Univ.), pp. 43-53.
Ford, C.W., I.M. Morrison, and J.R. Wilson. 1979. Temperature effects on lignin, hemicellulose, and cellulose in tropical and temperate grasses. Aust. J. Agric. Res. 30:621-633.
Frost, W.E., and N.K. McDougald. 1989. Tree canopy effects on herbaceous production of annual rangeland during drought. J. Range Mngt. 42:281-283.
Gardner, F.P., B.B. Pearce, and R.L. Mitchell. 1985. Physiology of crop plants. Iowa State University Press; Ames, IA.
Garrett, H.E. and L. Buck. 1997. Agroforestry practice and policy in the United States of America. Forest Ecology and Management 91:5-15.
Garrett, H.E., L.E. Buck, M.A. Gold, L.H. Hardesty, W.B. Kurtz, J.P. Lassoie, H.A. Pearson and J.P. Slusher. 1994. Agroforestry: An Integrated Land-Use Management System for Production and Farmland Conservation. USDA SCS, Washington, D.C. 59 p.
Garrett H.E. and W.B.Kurtz. 1983. Silvicultural and economic relationships of integrated forestry farming with black walnut. Agroforestry Systems 1(3):245-256.
Glickman, Dan, M. Gonzalez, D.M. Bay. 1999. 1997 Census of agriculture - State data. United States Department of Agriculture: National Agricultural Statistics Service.
Godsey, L.D. 2000. Economic budgeting for agroforestry practices. Agroforestry in Action #3-2000, University of Missouri Center for Agroforestry, Columbia, MO, 16 pgs.
Grado, S.C., C.H. Hovermale, D.G. St. Louis. 1998. A preliminary economic assessment of a silvopastoral system in south Mississippi. In: Proc., Southern Agroforestry Conference, Huntsville, AL. October 19-21, 1998.
Grado, S.C., C.H. Hovermale, D.G. St. Louis. 2001. A financial analysis of a silvopasture system in southern Mississippi. Agroforestry Systems 53(3):313-322.
Hall, L.M., M.R. George, D.D. McCreary and T.E. Adams. 1992. Effects of cattle grazing on blue oak seedling damage and survival. Journal of Range Management. 45:503-506.
Harwell, R.L. and C.W. Dangerfield, Jr. 1990. Sustaining use on marginal land: Agroforestry in the Southeast. In: (P. Williams, ed) Agroforestry in North America: Proceedings of the First Conference on Agroforestry in North America, 13-16 August, 1989, Department of Environmental

Biology, Ontario Agricultural College, University of Guelph, Guelph, Ontario, Canada. pp. 212-220.
Hawley, Ralph C. and Paul W. Stickel. 1948. Protection against domestic animals: grazing. In: Forest Protection. John Wiley & Sons, Inc., New York. pp. 240-256.
Henderson, S. and R.K. Dixon (eds.). 1993. Management of the terrestrial biosphere to sequester atmospheric CO_2. Inter-Research. 140 p.
Hershey, Frank A. 1991. The extent, nature and impact of domestic livestock grazing on Missouri woodlands. In: (H.E. 'Gene' Garrett, ed) Proceedings of the Second Conference on Agroforestry in North America; Springfield, MO. pp. 248-255.
Hintz, D.L. 1983. Benefits associated with feedlot and livestock windbreaks. USDA Soil Conservation Service, Midwest National Technical Center, Technical Note 190-LI-1, 15p. Lincoln, NE.
Holechek, J.L., M. Vavra, and J. Skovlin. 1981. Diet quality and performance of cattle on forest and grassland range. J. Anim. Sci. 53:291-298.
Hubbard, W.G., R.C. Abt, M.L. Duryea and M.G. Jacobson. 1998. Estimating the profitability of your non-timber forestland enterprise. University of Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, Circular 836, University of Florida, Gainesville, Florida. 13 p.
Huck, M.B., M.S. Kerley, H.E. Garrett, R.L. McGraw, J.W. Van Sambeek, and N.E. Navarrete-Tindall. 2001. Effect of shade on forage quality. In: (W. Schroeder and J. Kort, eds). Proc of 7th Biennial Conf. on Agroforestry in North America. pp. 125-135.
Husak, A.L., S.C. Grado. 2001. Monetary and wildlife benefits in a silvopastoral system. In: Proceedings of the 2000 Southern Forest Economics Workshop. Lexington, KY. March 28, 2000. pp. 167-175.
Kay, B.L. 1987. Long-term effects of blue oak removal on forage production, forage quality, soil, and oak regeneration. In: Proc. Symp. Multiple Use of California's hardwood resources. USDA Forest Serv. Gen. Tech. Rep. PSW-100. pp. 351-357.
Kelly, C.F., T.E. Bond, and N.R. Ittner. 1950. Thermal design of livestock shades. Agr. Eng. 31:601-606.
Kephart, K.D., and D.R. Buxton. 1993. Forage quality responses of cool and warm perennial grasses to shade. Crop Sci. 33:831-837.
Kephart, K.D., D.R. Buxton, and S.E. Taylor. 1992. Growth of cool and warm season perennial grasses in reduced irradiance. Crop Sci. 32:1033-1038.
Koch, N.E. and J.J. Kennedy. 1991. Multiple-use forestry for social values. Ambio v. 20:330-333.
Kurtz, W.B., H.E. Garrett, J.P. Slusher, and D.B. Osburn. 1996. Economics of agroforestry. MU Guide, Forestry #G 5021, University of Missouri Extension, University of Missouri-Columbia, 2 p.
Lamson, N.I., H.C. Smith, A.W. Perkey, and S.M. Brock. 1990. Crown release increases growth of crop trees. Research Paper, NE-635. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p.
Lantagne, D.O. 1991. Tree shelters increase heights of planted northern red oaks. GTR-NE-148. USDA Forest Service, Northeastern Forest Experiment Station pp. 291-298.

Lehmkuhler, J., E.E.D. Felton, D.A. Schmidt, K.J. Bader, A. Moore, M.B. Huck, H.E. Garrett and M.S. Kerley. 2002. Grazing during the establishment period: Methods of tree protection and impact of grazing on tree and animal performance. In: (W. Schroeder and J. Korts, ed's), Proceedings of the 7th North American Agroforestry Conference Aug. 12-15, 2001. Saskatchewan, Canada. pp. 135-143.

Lehmkuhler, J.W., M.S. Kerley, H.E. Garrett, B.E. Cutter, and R.L. McGraw. 1999. Comparison of continuous and rotational silvopastoral systems for established walnut plantations in southwest Missouri, USA. Agroforestry Systems (44): 267-279.

Lin, C.H., R.L. McGraw, M.F. George and H.E. Garrett. 2001. Nutritive quality and morphological development under partial shade of some forage species with agroforestry potential. Agroforestry Systems 53:1-13.
Lin, C.H., R.L. McGraw, M.F. George and H.E. Garrett. 1999. Shade effects on forage crops with potential in temperate agroforestry practices. Agroforestry Systems 44:109-119.
Lovelace, W. 1998. The root protection method (RPM) system for producing container trees. Combined Proceedings International Plant Propagators' Society. 48:556-557.
Lowrance, R.R. 1992. Groundwater nitrate and denitrification in a coastal plain riparian forest. J. Environ. Qual. 21:401-405.

Lundgren, G.K., J.R. Connor, and H.A. Pearson. 1983. An economic analysis of forest grazing on four timber management situations. Southern Journal of Applied Forestry 7(3), 119-124.

Marquis, D.A. 1988. Guidelines for regenerating cherry-maple stands. In: (H.C. Smith, A.W. Perkey, and W.E. Kidd, Jr., ed's) Proceedings, Guidelines for Regenerating Appalachian Hardwood Stands, 24-26 May 1988, Morgantown, W.Va Soc. Am. Pub. 88-03. pp. 167-188.

McCreary, D.D. and J. Tecklin. 2001. The effects of different sizes of tree shelters on blue oak growth. Western Journal of Applied Forestry 16(4): p. 153-158.

McDaniel, A.H., and C.B. Roark. 1956. Performance and grazing habits of Hereford and Aberdeen-angus cows and calves on improved pastures as related to types of shade. J. Anim. Sci. 15:59-63.

McIlvain, E.H., and M.C. Shoop. 1971. Shade for improving cattle gains and rangeland use. J. Range Mgt. 24:181-184.

Minckler, Leon S. 1961. Measuring light in uneven-aged hardwood stands. Technical Paper 184. U.S. Department of Agriculture, Forest Service, Central States Forest Experiment Station. 9 p.

Minter, W.F., R.K. Myers, and B.C. Fischer. 1992. Effects of tree shelters on northern red oak seedlings planted in harvested forest openings. Northern Journal of Applied Forestry 9(2):58-63.

Muller, C.J.C., J.A. Botha, W.A. Smith and W.A. Coetzer. 1994. Production, physiological and behavioral responses of lactating friesian cows to a shade structure in a temperate climate. In: (R. Budklin, ed.) Dairy Systems for the 21st Century. Proceedings, Third International Dairy Housing Conference. February 2-5, 1994, Orlando, FL

Nair, R.P.K. and V.D. Nair. 2002. Carbon sequestration in agroforestry systems. In: (I. Kheoruenromne, ed) Soil Science: Confronting New Realities in the 21st Century, Proceedings of the 17th World Congress of Soil Science, 14-21 August, 2002, Thailand. Volume I, Symposium no. 10, Paper no. 989, 13 pgs.

Neel, L.R. 1939. The effect of shade on pasture. Tenn. Agr. Exp. Sta. Circular #65. 2p.

Noweg, T.A and W.B. Kurtz. 1987. Eastern black walnut plantations: an economically viable option for conservation reserve lands within the corn belt. No. J. Appl. For. 4:158-160.

Ostrofsky, R.S., R.S. Seymour, and R.C. Lemin, Jr. 1986. Damage to northern hardwoods from thinnings using whole-tree harvesting technology. Can. J. For. Res. 16: 1238-1244.

Parcell, J. 2000. Carbon sequestration and its value for Missouri producers. Online publication http://agebb.missouri.edu/mgt/carbon.htm [last accessed 11/20/2001].

Patric, J.H. and J.D. Helvey. 1986. Some effects of grazing on soil and water in the eastern forest. NE-GTR-115. Bromall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 25 p.

Pearson, H.A. 1990. Silvopasture: Forest grazing and agroforestry in the southern coastal plain. Proceedings of Practical Agroforestry in the Mid-South Conference. West Memphis, AR pp. 25-42.

Raedeke, A, J. Green, S. Hodge, and C. Valdivia. 2003. Farmers, the practice of farming and the future of agroforestry: An application of Bourdieu's concept of field and habitus. Rural Sociology 68(1):64-86.

Reisinger, T.W. and P.E. Pope. 1991. Impact of timber harvesting on residual trees in a central hardwood forest in Indiana. In: 8th Central Hardwood Forestry Conference. USDA Forest Serv. Gen. Tech. Rep. NE-148. pp. 82-91.

Roberts, E.N. 1926. Wyoming forage plants and their chemical composition studies. No. 7. Effects of altitude, seasonal variation, and shading experiments. Wyoming Agr. Exp. Sta. Bull. 146.

Sander, I.L. 1979. Regenerating oaks with the shelterwood system. In: Proceedings Regenerating Oaks in Upland Hardwood Forests, The 1979 J.S. Wright For. Conf. (Purdue Univ.), pp. 54-60.

Schlesinger, R.C. 1978. Increased growth of released white oak poles continues through two decades. Journal of Forestry 76(11): 726-727.

Shiflet, T.N. 1980. What is the resource? In: (R.D. Child and E.K. Byington ed's) Southern Forest Range and Pature Resources. Winrock International, Morrilton, AR. pp. 17-28.

Shigo, A.L. 1979. Tree decay -- an expanded concept. USDA Forest Service. Agriculture Information Bulletin (419). 73p.

Shigo, A.L. 1966. Decay and discoloration following logging wounds on northern hardwoods. Research Paper, NE-47. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 43 p.

Smith, W.B., J.S. Vissage, D.R. Darr, and R.M. Sheffield. 2001. Forest resources of the United States, 1997. Gen. Tech. Rep. NC-219. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 190 p.

Smith, H.C. and G.W. Miller. 1991. Releasing 75- to 80-year-old Appalachian hardwood sawtimber trees: 5-year d.b.h. response. In: (L.H. McCormick and K.W. Gottschalk, ed's); 8th Central Hardwood Forest Conference; Pennsylvania State University; University Park, PA. pp. 402-413.

Smith, H.C. 1966. Epicormic branching on eight species of Appalachian hardwoods. Research Note, NE-53. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 4 p.

Smith, R.M. 1942. Some effects of black locusts and black walnuts on southeastern Ohio pastures. Soil Science 53(5):385-398.

Spain, J.N., J. Zulovich and D.K. Hardin. 1987. Heat stress on a commercial dairy farm: An economic evaluation of cooling. In: (R.W. Botcher and S.J. Hoff, ed's.) Livestock Environment V, Volume II, Proceedings of the Fifth International Symposium, May 29-31, 1997. Bloomington, MN. pp. 936-941.

Standiford, R.B. and R.E. Howitt. 1993. Multiple use management of California's hardwood rangelands. Journal of Range Management 46(2):176-182.

Stephenson, W.H. 1954. North Carolina's beef, pork and poultry trade. In: A basic history of the old south. D. Van Nostrand Co., Inc., Princeton, NJ. p. 107-109.

Stokes, B.J., R.A. Kluender, J.F. Klepac, and D.A. Lortz. 1995. Harvesting impacts as a function of removal intensity. In: XX IUFRO World Congress on Forest Operations and Environmental Protection. Tampere, Finland. pp. 207-216.

Van Tassell, Larry W., E.T. Bartlett, and J.E. Mitchell. 2001. Projected use of grazed forages in the United States: 2000 to 2050: A technical document supporting the 2000 USDA Forest Service RPA Assessment. Gen. Tech. Rep. RMRS-GTR-82. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 73 p.

Ward, W.W. 1966. Epicormic branching of black and white oaks. Forest Science 12(3): 290-296.

Webster, A.J.F. 1970. Direct effects of cold weather on the energetic efficiency of beef production in different regions of Canada. Canadian Journal of Animal Science. 50:563-573.

Wolters, G.L. 1973. Southern pine overstories influence herbage quality. J. Range Mgt. 26:423-425.

Worstell, D.M., and S. Brody. 1953. Environmental physiology and shelter engineering. Mo. Agr. Exp. Sta. Res. Bul. #515.

Zinkhan, F.C. and D.E. Mercer. 1997. An assessment of agroforestry systems in the southern USA. Agroforestry Systems 35:303-332.