AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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While successful timber production systems accelerate tree growth at the expense of understory components, successful agroforestry systems maximize the total system production, including the understory component. This study examined the effect of trees on understory biomass production to determine if aboveground interactions or underground factors produce the greater effect. For 1993 and 1994, a series of transects using random trees for starting points were established before sheep grazed the agroforests. Each transect consisted of six or seven plots that were sampled for biomass by clipping, drying, and weighing of herbaceous material. Transects extended perpendicular to tree rows, approximately north and south, with plots, 0.10 m², every 0.5 m starting 0.5 m from the tree trunk. Transects were also clipped from pastures. Near-earth, remotely-sensed imagery was obtained before grazing periods. Two arrays, each consisting of six photosynthetically active radiation (PAR) sensors, were used to measure the tree's effect on available solar energy at locations matching clipped plots. A geographic information system (GIS) database was also developed for agroforestry plots. Data from these sources were used in regression analysis. Four mathematical growth models were developed using vegetative indices created from remotely sensed data. Individual best-fit agroforest models predicted forage yields within 135 kg/ha (5.0, 5.8, and 8.9%) of actual harvested plots. Regression analysis of PAR data produced an anisotropic pair of models for available solar energy, one for each direction from the

tree. These models demonstrated the anisotropic nature of available solar energy in our agroforests. However, pattern analysis of clipping data showed strong isotropic forces dominating understory growth. Decreased production in row middles, detected by both clipping and remote sensing analysis, suggested animal use patterns, in the form of trails, may significantly affect forage production in silvopastoral systems. Because aboveground tree effects are primarily anisotropic while underground factors are isotropic, we conclude that underground competition for soil moisture and/or nutrients controls understory production in young open-canopy agroforests. It appears that agroforest manipulations that seek to manage shade on understory herbaceous vegetation in open canopy silvopastures will have limited effects compared to those that manipulate tree water and nutrient use.

Spatial Patterns of Tree Effects on Pasture Production
in Open Canopied Agroforests

by

Norman Rex Harris

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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Norman Rex Harris, Author

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CONTRIBUTION OF AUTHORS

Norman Harris was involved in the experimental design, analysis, and writing of each manuscript. Dr. Steven Sharrow was involved in the experimental design, analysis, and writing of each manuscript. Dr. Douglas Johnson was involved in the design of the sensor and in the collection and analysis of remotely sensed data.

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DEDICATION

This thesis is dedicated to the loving memory of my grandparents, Harold and Mae Henderson. "Grandma and Grandpa, I finally went back to school."

Spatial Patterns of Tree Effects on Pasture Production
in Open Canopied Agroforests

Chapter 1

Introduction and Literature Review

Humans have a long and close relationship with trees and forest products. The ability to start fires and maintain them using wooden fuels was a major leap in human evolution. Wooden sticks were among the earliest of weapons, useful in the hunt, and also in the conquest of other people. Wood has been a major building material throughout human history. In earlier times, the forest was viewed as an endless resource never feeling the impact of its human inhabitants, or as an impediment to agriculture or other land uses. It is now becoming apparent that forests may have been impacted beyond the limits that natural regeneration can replenish. Human intervention is needed to restore this dwindling forest resource. Today's concerns about global warming have further emphasized the role of forests in global cycles such as sequestering greenhouse gases. This has made reforestation even more critical (Postel and Heise, 1988). The replenishment of our dwindling forest resources has now become a global priority.

In order to expedite the regrowing of forests, past research dealing with the timber/herbage interface has concentrated on methods of optimizing timber production at the expense of the herbaceous and shrub understory components. The silvicultural goal was maximum tree growth, which required a virtual elimination of competition for the available site resources: light, moisture, temperature, and nutrients (Wray, 1987). This research lead to many practices currently used in the commercial forest industry. Planting trees in a uniform grid pattern dominates the industry today. It is meant to decrease intraspecific competition between individual trees while increasing interspecific competition between trees and understory vegetation (Avery and Gordon, 1983). Its goal is to shift the advantage to the trees for obtaining available site resources. Another technique is to "release" trees from competition with chemical or

physical suppression of the understory plants. Ideally, rapid tree growth then allows the silvicultural crop to dominate the site before the understory components can recover and repopulate (Wray, 1987). These strategies have proven very successful in increasing tree growth rates. However, even with this acceleration in growth, the time required to grow a tree can exceed a human life span. In western Oregon, the time span required to grow a Douglas fir to a marketable size, twenty years to commercial thinning, sixty or more years until harvest, requires a long-term commitment and a major investment of money (Sharrow and Fletcher, 1994). This reality has led to greater interest in multi-crop agroforestry systems. Agroforestry systems combine tree production with the joint production of agricultural crops and/or animals (Lundgren, 1982). This helps offset the burden of long-term silvicultural debt by providing short-term agricultural income (Nair, 1985). Attention, especially in developed countries, is now directed toward the use of quicker maturing understory components to generate an earlier, and even larger return for investors (Carruthers, 1990).

Agroforestry systems are not a product of modern scientific theory but have been practiced by indigenous farmers throughout the world for centuries because they make practical sense (Nair, 1985). Over the millennia, the Kayapo Indians of Brazil's Amazon Basin have developed an extremely effective agroforestry system without any outside influence (Posey, 1985). The ancient Romans planted grains among the grapevines that twined through the olive trees in an attempt to produce maximum yields per unit of land (Winkler et al., 1974). Ideally, a combination of plants would utilize site resources non-competitively by way of differences in rooting depth or in season of growth, thus maximizing the efficiency of crop production (Buck, 1986).

A strictly, scientific definition of agroforestry stresses two differences between it and other land use systems. First, woody perennials must be deliberately grown on the same land as agricultural crops and /or animals. Second, there must be significant interaction between components, positive and/or negative (Lundgren, 1982). However, scientific knowledge of these systems is limited. The interactions between components

has been only superficially explored. For success, components must interact to the overall benefit of the agroforestry system. Overall success for an agroforestry system is based on both abiotic and biotic factors, such as topography, weather, and plants/animals. It is also influenced by strong economic and social forces. This research investigates some of the abiotic and biotic factors but does not explore the economic or social aspects.

Agroforesters group systems based upon their structural components into three types; agrosilviculture (trees + crops), silvopastoral (trees + livestock), and agrosilvopastoral (trees + crops + livestock) (Nair, 1985). Of these three types, agrosilvopastoral systems are the most complex, both in their structure and in their management. Forest, forage crop, and livestock enterprises exist as strong separate industries in both the western and southeastern United States. Therefore, it is not too surprising that the most common agroforestry system found in the Pacific Northwest, and in the United States in general, incorporates livestock, usually sheep or cattle, with timber production (Logan, 1983, Gold and Hanover, 1987). Well managed agroforestry systems can sustainably increase land productivity, improve cash flow, and increase the diversity of plants and animals present on western Oregon hill lands (Sharrow and Fletcher, 1994). The understory vegetation in these systems is generally a combination of established pasture grasses and seeded legumes. Legumes, in particular, may increase weight gains of livestock while supplying needed nitrogen for trees (Logan, 1983, and Anderson et al., 1988). This plant population also covers the soil, protecting it from wind and water erosion. However, uncontrolled pasture growth may compete with young trees for soil moisture, and provides a habitat for small mammals that gnaw on trees. Agroforesters strive to obtain more production per unit land by balancing livestock production with timber production (Logan, 1983). Livestock convert forage into meat or other products such as wool, milk, or dung. This grazing, in turn, reduces the competitive effects of the pasture on trees, reduces invasion by weedy plants, and recycles forage nutrients as dung and urine.

Livestock grazing patterns as well as pasture production may be affected by the proximity to a tree. This complex set of biological interactions among agroforest components is reflected in an equally complex spatial structure. Successful agrosilvopastoral design and management relies upon a fundamental understanding of how spatial structure relates to the agroecosystem processes of competition, succession, nutrient cycling, carbon flow, and hydrology. Agroforesters manage agroecosystem processes primarily through manipulating system spatial structure.

Discussion

Trees are a fundamental structural element in any agroforest. Their health and well-being is of primary importance for land managers and system operators. Agroforestry systems in Oregon emphasize the quantity and quality of wood production. Therefore, any limitations to tree growth are a major concern. The primary resources that might limit plant/tree growth at various times in the growing season are water, nutrients, and solar energy (Salisbury and Ross, 1992, Harper, 1977, and Buck, 1986). Those areas where the strongest interactions occur between the tree and understory components are of particular interest. The key to maximizing overall agroforest benefits requires an intimate understanding of this relationship between a tree and the understory plants surrounding it. We can then use this understanding in designing systems that obtain a better resource sharing in time and space (Buck, 1986).

Plant interactions can be quite different when the relative importance of a primary resources shifts substantially, such as the importance of water in a wet year compared to a drought year. Quantification of many confounding variables that also constantly change in their ranking of relative importance, such as water, nutrients, or understory composition, presents a major problem in plant competition studies. The connected nature of the landscape, where the individual components function together, much like a single entity, makes the measurement of a single, specific response

extremely difficult (Harper, 1977). For example, cutting off the lower branches of an agroforestry tree increases the available sunlight reaching the understory leading to an increase in forage production (Logan, 1983, Anderson et al., 1988, and Buck, 1986). However, pruning also decreases the transpirational surface of the tree that significantly alters its internal water balance and reduces tree growth (Buck, 1986, and Yunusa et al., 1995a). These alterations may also act to increase forage production by reducing water and nutrient use by trees, making the exact quantification of the benefit from the increased solar energy complicated. In a similar fashion, subterranean clover (*Trifolium subterraneum L.*) increases the amount of soil nitrogen available for plant growth (Logan, 1983, and Tisdale et al., 1985). It dies in early summer, decreasing the water competition within the plant population (Harper, 1977). Measuring the effect of increased nitrogen versus the effect of greater water availability on tree growth is a difficult task because the three major processes involved in nutrient uptake, diffusion, mass flow, and root contact, are affected by soil moisture levels (Kramer, 1980, and Tisdale et al., 1985). Grazing also affects growth, persistence, and proportion of pasture plants. Frequent defoliation is especially important in maintaining mixed grass/legume stands. It keeps the grass from shading out the legume component (Whitehead, 1970). Other less important resources may become amplified through their effect on primary resource acquisition. Changes in soil atmosphere, the pore spaces filled with air, are magnified through their effect on moisture and nutrient uptake (Tisdale et al., 1985).

Many studies have been done on the relationship between tree basal area, or cover, and understory production. Sharrow (1991) reported that 10-year-old conifer trees have a detrimental effect on forage production for a distance approximating 2 canopy diameters with no effect apparent beyond that distance. Other work (Woods et al. 1982, Cameron et al. 1991, Joyce and Mitchell 1989) has shown a similar pattern of detrimental effects that lessen with increasing distance from the tree. A similar effect was predicted by a model developed by Scanlon (1992) that used factors relating to both beneficial and detrimental responses to predict the effect of distance from tree on forage production. Both beneficial and competitive effects accrue from the interactions

between plants as they attempt to use the resources available to them. The exact response of a plant to these effects varies by tree and individual forage species. Pieper (1990) found that production of cool season grasses increased with canopy cover of pinyon-juniper trees while that of warm season grasses declined.

Pattern analysis can often separate effects qualitatively, but a quantification of specific effects can be nearly impossible to isolate, and the proper scale of confounding factors difficult to discern (Isaaks and Srivastava, 1989). Arnold (1964) and Everett et al. (1983) showed a distinct zonation in understory production around pinyon-juniper. Everett et al. (1983) also noted these changes were a successional reorganization of existent vegetation rather than invasion by other species. Tree effects on individual species varied with tree size, topographical aspect, and slope position relative to stem. This zonation graphically displayed individual species successes in obtaining growth resources from the area near trees. However, dominance is not a static condition. Variation in the timing of climatic events, such as rainfall, can turn a winning strategy one year into a loser the next year (Harper, 1977). Agroforestry designs attempt to minimize competition and to maximize facilitation between the tree and the understory components for the most common conditions (Sharrow and Fletcher, 1994).

For convenience, we can divide forces acting upon a plant into an aboveground factor, primarily solar energy, and an underground factor, primarily available nutrients and water. Research conducted in dry climates suggest the most limiting factor for forage production is interspecific competition for moisture (Ong et al., 1991). Riegel (1989) found underground factors to be important in limiting forage production under semi-arid pine forests of northwestern Oregon. Krueger (1981) stated that, in dry years, moisture would be the most limiting factor in eastern Oregon forests. However, the work of Young and Smith (1982 and 1983) showed that either light or water could be the most limiting factor depending on environmental variables during that year. The importance of solar radiation in their research might reflect their cold subalpine sites and not be applicable to other warmer locations. In southwestern Australia, on a site

more comparable to western Oregon, Anderson and Batini (1979) indicated that light was the limiting factor for understory forage growth with little apparent competition with trees for moisture. An important limiting factor in the maritime climate of the Willamette Valley might be the availability of solar energy. This resource is made more important by the low solar altitudes and the long shadows typical during the early part of the growing season at this latitude and the many overcast, low-light days (ASHRAE, 1991).

A way of understanding the interplay of these natural forces is to examine the spatial patterns that result from them (Isaaks and Srivastava, 1989). Pattern studies in an agroforest system are difficult because of the complexity (numerous component configurations), the large area required, and the long time period between management actions and growth responses (Sharrow, 1991). The general dicotomy, of aboveground and underground factors, can be related to the two primary force patterns: isotropic and anisotropic. An isotropic force acts in all directions the same way, while an anisotropic force acts differently, with a different magnitude, in different directions (Isaaks and Srivastava, 1989, and Eastman, 1995). Clipping data by Yunusa et al (1995b) for a ryegrass/clover understory and a lucerne understory grown under Monterrey pine (*Pinus radiata*) showed basic isotropic patterns for most of the clipping periods. However, a pure ryegrass understory exhibited a distinct anisotropic pattern for these same periods. Data for northwestern Oregon (Sharrow, 1991) showed isotropic patterns that were regression modeled (R^2=0.87) based on distance from tree. The work of Scanlon (1992) in a mesquite-pinyon system and in an eucalypt-dominated system produced isotropic models with concentric facilitative and competitive zones. Other work (Arnold, 1964, and Everett et al., 1983) showed isotropic patterns of growth interspersed with anisotropic patterns indicating individual specie preferences. In our research, forage biomass forms a spatial pattern radiating outward from a tree located in the center. Moisture/nutrient interactions are based upon the root system which, when viewed from the top and given no major soil differences or physical obstacles, radiates in all directions from the tree trunk (Tisdale et al., 1985, and Sutton, 1969). Tree roots

Figure 1.1. Examples of Isotropic Force and Anisotropic Force.

Isotropic Force

Anisotropic Force
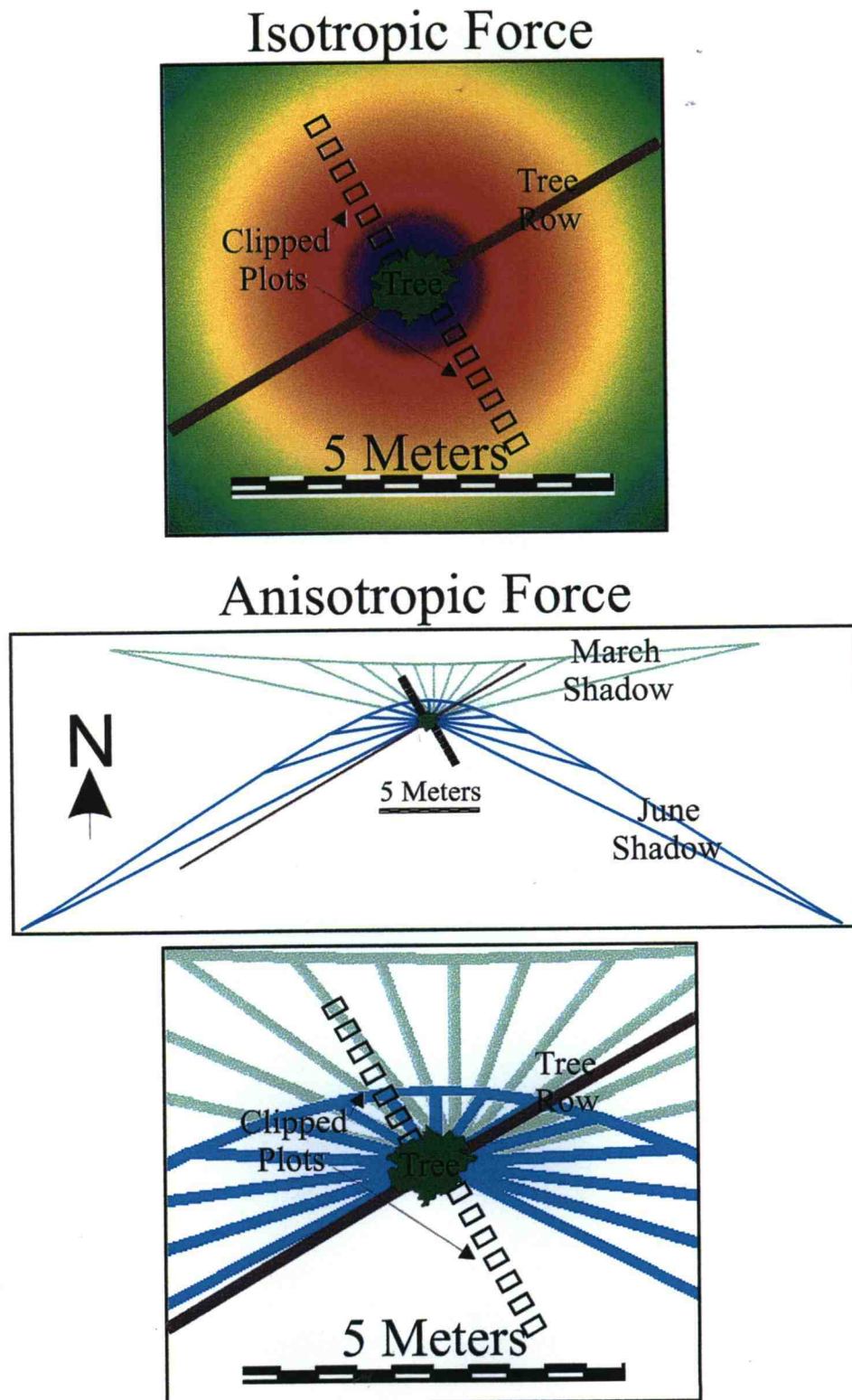
penetrate deeper soil layers extracting soil water and nutrients from this area beyond the reach of shallow rooted pasture systems (Ball et al., 1979, and Glover and Beer, 1986). On the other side, the dense mat of grass roots is efficient in capturing surface moisture and nutrients released by litter decomposition (Glover and Beer, 1986). A general water/nutrient model dictates that all roots, large and small, will function in the same manner (Sutton, 1969). Therefore, patterns of forage biomass responding to nutrient or water competition with a centrally located tree should be isotropic (Figure 1.1) in nature. If the spatial patterns show few differences between north and south, then the primary acting forces are isotropic in nature. However, distinctly isotropic patterns can often indicate multiple isotropic forces working in concert (Eastman, 1995). In our case, isotropic forces could be indicative of, not only soil resources, but also livestock impacts. Both north and south sides of our agroforestry trees are equally available to the livestock for grazing, so the animal use pattern across alleys would also show as an isotropic force, unless livestock were responding to shade. Examination of spatial patterns separates acting forces into basic isotropic and anisotropic components, but it does not clearly indicate if the pattern is the result of one or more than one co-acting forces (Isaaks and Srivastava, 1989).

A tree in the northern hemisphere casts a shadow predominantly to its north side producing a distinctly anisotropic pattern of available solar energy (ASHRAE, 1991). If south and north sides of a tree do not show similar forage production patterns, the anisotropic response might suggest tree shadows as an important factor in tree/understory interactions and understory production. It should be noted that shade has other effects beside limiting available energy for photosynthesis. The presence or absence of a species, the size and shape, and even nutritive content are determined, in part, by light (Krueger, 1981). Anderson and Batini (1983) note that nitrogen-fixing legumes do not tolerate shading and are at a disadvantage compared to competing grasses when low light levels exist. Shade also lowers plant and soil temperatures with varying effects on vegetation moisture demands and on growth (Tisdale et al., 1985). Heat stress is one of the primary forces keeping plants from attaining their full yield

potential (Buck, 1986, and Kramer, 1980). Wilson (1986) found that shade can actually increase production during drought conditions. The spectral quality of solar energy is also altered by refraction and reflection as it passes through the upper canopy. This spectral change can effect plant phenology and morphology as well (Buck, 1986, and Salisbury and Ross, 1992). Wind and precipitation (rain shadows) can also produce anisotropic patterns. However, at our study site, these patterns are oriented, predominantly, down the tree rows and not across row centers (Taylor, 1997, personal communication).

Our study attempts to use low-level remote sensing technology to identify and quantify tree and site spatial variables that exert major influences on pasture growth. It is hoped that this detailed description of spatial vegetation and environmental patterns will suggest the nature and intensity of the interactions between agroforest components as they share resources in time and space. Remote sensing is the science and art of gathering information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand and Keifer, 1987). Accurate analysis of remotely sensed plant community data is dependent on an understanding of the reflectance/absorbance of energy from vegetation.

Energy in the near infrared range (0.70 μm to 1.30 μm) is reflected strongly, with reflectance reaching 50 percent of incident radiation (Knipling, 1970). The reflectance of infrared is related to the structural complexity, ie. cell wall interfaces, of the vegetation (Grant, 1987). This complexity varies considerably between species. Dicots, broadleaf plants, reflect greater amounts of infrared than monocots, grasses (Salisbury and Ross, 1992). Structurally-caused reflective differences between species form the basis of most classification procedures (Chen et al., 1995, and Knipling, 1970). Visible light (0.40 μm to 0.70 μm), composed of the primary colors, red, green, and blue, is reflected weakly by vegetation with reflectance values ranging from 5 to 20 percent of incident radiation. Energy in the blue and the red ranges is absorbed by plant

chlorophyll and is used to power the photosynthetic apparatus (Salisbury and Ross, 1992). Therefore, dense, high chlorophyll-content vegetation will absorb more red and blue energy and will reflect less than sparse or low chlorophyll-content vegetation. Where the understory is of a homogeneous composition (ie. agronomic forage crops and pastures), reductions in reflectance form a gradient indicating greater biomass.

Certain plant species reflect noticeably more blue light than others and appear as a blue-green color. Because of these species-related differences, the blue band potentially contains more information for some vegetation types than does the red band. Tucker (1977), for instance, noted that wet or dry weight biomass had its strongest correlation with the blue band (0.35 μm to 0.44 μm). However, selective atmospheric *Rayleigh* scatter, which causes the blue color of the sky, makes blue light hard to accurately detect and measure. The longer the atmospheric pathway between object and sensor, the more severely the blue channel is distorted by scatter "noise." Past emphasis on satellite and high-altitude aerial photography has rendered blue band data relatively unimportant. So much so, that many satellite systems, such as the SPOT, have abandoned blue band detection entirely, and panchromatic imaging uses only the red and green wavebands (Lillesand and Keifer, 1987) For this reason, most vegetation indices are based on near-infrared/red band ratioing (Richardson and Everitt, 1992). However, when the sensor is located less than 150 meters from the target as in near-earth sensing, the potential usefulness of blue band data increases considerably.

Researchers and managers have used remote sensing to evaluate rangelands since the late 1930s. This spatial data was never fully utilized because of limitations in storing and analyzing it (Anderson, 1996). The development of personal computers produced hardware capable of handling large amounts of data, and, in the early 1970s, geographic information systems (GIS) were developed for manipulation and analysis of spatial data (Dangermond, 1991). GIS software stores geographically linked information as a series of numbers within different layers that can be mathematically manipulated to produce other information. The ability to combine information from

different sources and to create new information is what distinguishes GIS from other mapping systems (Anderson, 1996).

The collection of accurate spatial data has been greatly improved through the development of another computer-based technology, Global Positioning Systems (GPS) (Deckart and Bolstad, 1996). Developed primarily for military use, GPS has been rapidly adopted for a myriad of private and public uses (Anderson, 1996, and Deckard and Bolstad, 1996). GPS is based on a system of twenty-four navigational satellites orbiting the earth. Satellite signals are processed using a GPS receiver to obtain real world coordinates for any point on the earth (Trimble, 1991). Errors in the satellite clock, satellite positions, receiver clock, and atmospheric delays of the signals degrade accuracy (Deckard and Bolstad, 1996). Accuracy is further degraded deliberately because of military concerns about security. A standalone GPS receiver obtains position estimates that are accurate to within 100 meters (Anderson, 1996, and Trimble, 1991). Differential GPS receivers provide much more precise positions by referencing position estimates against a known reference point. The difference between position estimates received by a referenced base station and its known location are calculated and used to correct position estimates simultaneously collected by a roving GPS receiver. Differentially corrected positions are accurate to less than 5 meters (Anderson, 1996, Deckart and Bolstad, 1996, and Trimble, 1991). According to Anderson (1996), "When used in combination, GIS, GPS, and remote sensing technologies provide the spatial framework, data analysis, and location assessment tools needed to combine information sources, create new information, validate results, and provide visual representations of the spatial dynamics for an area."

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Chapter 2

Isotropic Patterns Dominate Understory Production
in a Pacific Northwest Agroforestry System

Norman R. Harris and Steven H. Sharrow

Abstract

A successful agroforestry design balances production of short-term products, such as livestock and/or crops, with longer-term growth of woody plants. The most common agroforestry system in the United States is a silvopastoral system that incorporates livestock, usually sheep or cattle, with timber producing trees. Our agroforest plantations are Douglas-fir trees planted in a subclover/perennial ryegrass pasture. Designing silvopastures demands an intimate knowledge of the complex interactions between trees, pasture, and their environment. Those areas where competition occurs between agroforestry components for limited resources, are of particular importance. The primary limiting resources for plant growth are solar energy, water, and nutrients. These resources can be grouped into aboveground and underground factors. Underground factors, available water and nutrients, act as an isotropic force, a force that acts equally in all directions around trees. Shadow modeling indicates that solar energy acts as an anisotropic force, a force that acts with different magnitudes in different directions. Photosynthetically active radiation (PAR) data was collected using two arrays of sensors placed to the north and south of random trees. Biomass samples were collected by clipping plots along transects placed to the north or south of random trees. Samples were obtained twice each year before the agroforests and pastures were grazed by sheep. PAR data and regression modeling confirmed that solar energy acts as an anisotropic force in our silvopastures. Spatial analysis of clipping data during an unusually wet spring, and a more typical spring suggests that environmental factors such as precipitation interact with structural elements such as trees to produce forage production patterns. These differences in patterns can be traced to changes in the relative importance of aboveground and belowground resources. Combined data for the two years showed an overall strong isotropic pattern of increasing forage production with increasing distance from trees. Forage production patterns were predominately isotropic in both early and mid-late spring both years, suggesting that trees and pastures were primarily competing for underground resources, probably soil moisture and nutrients, rather than for light. However, some anisotropic

forces were evident during mid-late spring in 1994. Based on these observations, agroforest manipulations that seek to manage shade effects on understory herbaceous vegetation in open canopy silvopastures will have limited effects compared to those that manipulate tree water and nutrient use.

Introduction

Trees have been an important human resource for many thousands of years. Historically, the forest resources seemed to exist in unlimited amounts, never feeling the impact of humans. However, today with the advent of satellite imagery the impacts are easily seen, and the replenishment of our dwindling forest resources has become a priority. Concerns about global warming have further emphasized the role of forests in sequestering greenhouse gases and have made reforestation even more critical (Postel and Heise, 1988). The time span for growing a tree to a marketable size, twenty years to commercial thinning, sixty or more until harvest in western Oregon, requires a long-term commitment and investment of money (Sharrow and Fletcher, 1994). Agroforestry systems lessen the burden of this long-term debt through a multi-product approach (Nair, 1985). Agricultural products may be marketed during the early timber growth period to generate short-term cash revenues. The most common agroforestry system found in the Pacific Northwest, and in the United States in general, incorporates livestock, usually sheep or cattle, with timber production in a silvopastoral design (Logan, 1983, and Gold and Hanover, 1987). Well-managed agroforestry systems can sustainably increase land productivity, improve cash flow, and increase the diversity of plants and animals present on western Oregon hill lands (Sharrow and Fletcher, 1994). The production of livestock is dependent on understory forage grown in the interspace between trees. Improved forage species are sometimes planted to maximize livestock production as well as to improve tree growth. Legumes, in particular, may increase weight gains of livestock while supplying nitrogen for trees (Logan, 1983, and Anderson et al., 1988).

Previously, foresters dealt with methods of optimizing timber production at the expense of the herb and shrub understory. This work lead to many developments in commercial forest management. The use of a uniform planting grid dominates the industry and is meant to decrease intraspecific competition between trees while it increases interspecific competition between trees and understory vegetation (Avery and Gordon, 1983). Chemical or physical suppression of the understory plants is often used to "release" young trees from competition. Ideally, rapid tree growth then allows the silvicultural crop to dominate the site before the understory components recover and repopulate (Wray, 1987). The ultimate goal was to shift the advantage to the tree for obtaining available site resources. Agroforesters strive to harmonize resource partitioning between trees, understory plants, and animals in time and space (Buck, 1986) so that overall system productivity is increased. The key to achieving this goal is an intimate understanding of the spatial relationship of resource capture between a tree and the understory plants surrounding it. Of particular interest are the interfaces where competition for various limited growth resources might occur. The primary resources that might limit plant growth at various times in the growing season are water, nutrients, and solar energy (Salisbury and Ross, 1992, Harper, 1977, and Buck, 1986). Plants with the best strategy to acquire and accumulate these resources will thrive, while their competitors will decline (Harper, 1977).

Pattern studies in an agroforest system are difficult because of the numerous component configurations, the large area required, and the long time between management changes and response (Sharrow, 1991). A potentially useful way to investigate the relative influence of natural forces is to examine the spatial patterns that result from them. Spatial pattern analysis often has been more successful in separating effects qualitatively, rather than quantitatively (Isaaks and Srivastava 1989). In our case, forage production forms a spatial pattern radiating from the tree stem that can be analyzed to determine the types of forces that shaped it (Isaaks and Srivastava, 1989). Aboveground and underground factors may be separated by associating them with the two primary force patterns, isotropic and anisotropic. An isotropic force acts

symmetrically in all directions, while an anisotropic force acts differently or with a different magnitude, in different directions (Isaaks and Srivastava, 1989, and Eastman, 1995). Moisture/nutrient interactions are based upon the root system which, when viewed from the top and given no major soil differences or physical obstacles, radiates symmetrically in all directions from the trunk (Tisdale et al., 1985, and Sutton, 1969). Therefore, patterns of forage growth responding to nutrient or water competition with a centrally located tree would be isotropic. If spatial biomass patterns show few differences between north and south sides of a tree, then it could be inferred that the primary forces are isotropic in nature. Distinctly isotropic patterns can often indicate multiple isotropic forces working in concert (Isaaks and Srivastava, 1989, and Eastman, 1995), or theoretically, several counterbalancing anisotropic forces. In our case, isotropic forces could include both soil resources and livestock impacts. Livestock used both north and south sides of our tree rows equally. Therefore, animal use patterns along alleys might appear as an isotropic force. However, a tree in the northern hemisphere casts a shadow predominantly to its north side (ASHRAE, 1991). If forage production patterns south and north of a tree differ, this anisotropic response would suggest tree shadows are an important factor in tree/understory interactions. It should be noted that shade has other effects beside limiting energy for photosynthesis. Shade also lowers plant and soil temperatures with varying effects on vegetation moisture demands and on growth (Tisdale et al., 1985). Heat stress is one of the primary forces keeping plants from attaining their full yield potential (Buck, 1986, and Kramer, 1980). Everett et al. (1983) and Wilson (1986) found that shade can actually increase production of certain species, especially under drought conditions. The spectral quality of solar energy is also altered by reflection and refraction as it passes through the upper canopy. This spectral change can alter plant phenological development (Buck, 1986, and Salisbury and Ross, 1992).

Research conducted in drier climates than western Oregon suggest the most limiting factor for forage production in an open canopy forest is interspecific competition for moisture (Ong et al., 1991). Riegel (1989) found underground factors to

be most important in limiting forage production under a previously open canopy, xeric

pine forest which had closed canopy as a result of fire exclusion in northwestern

Oregon. Understory forage production was most limited by competition with trees for

soil nutrients during the early spring, and for soil moisture as soils dried in late spring.

Krueger (1981) stated that moisture is probably the most limiting factor in the forests of

eastern Oregon in dry years. Arnold (1964) and Everett et al. (1983) observed distinct

rings of understory production around pinyon pine and juniper trees. Zones were

believed to be the result of a successional reorganization of existing vegetation rather

than invasion by outside species (Everett et al., 1983). Although tree impacts on total

understory production were predominately isotropic, effects on individual species were

strongly anisotropic. They varied with tree size, topographical aspect, and slope

position relative to the stem. These zones graphically display individual species success

in obtaining sufficient growth resources near the tree. Clipping data by Yunusa et al

(1995b) for a ryegrass/clover understory, and a lucerne understory grown beneath

Monterrey pine (*Pinus radiata*) showed basic isotropic patterns for most of the clipping

periods. However, a pure ryegrass understory exhibited a distinct anisotropic pattern for

these same periods, possibly reflecting species differences in resource demands. Data

for western Oregon silvopastures (Sharrow, 1991) showed isotropic patterns which were

regression modeled (R^2=0.87) based on distance from tree. The work of Scanlon (1992)

in mesquite and in eucalypt dominated systems produced isotropic models with

concentric facilitative and competitive zones which both decreased with distance from

trees. Observed forage production reflected the net effect of these two processes.

Under more mesic conditions in southwestern Australia, Anderson and Batini (1979)

concluded that "light reduction seems to be the only factor seriously reducing pasture

production" in a young, open canopy, pine forest. They felt there was little apparent

competition between pasture and trees for soil moisture. Early spring in western Oregon

is cool and rainy. Low solar altitudes, long shadows typical during the early part of the

growing season at this latitude, and the many overcast low-light days (ASHRAE, 1991)

favor competition for light during early spring. However, low air and soil temperatures

also limit growth and affect the response to light. Conversely, generally higher amounts

of incoming solar radiation, higher air and soil temperatures, and less precipitation during the late spring should emphasize competition for soil moisture. Therefore, light effects might be more pronounced during the first portion of the growing season then shifting to moisture effects during the second half. Our study attempts to use spatial analysis of forage production around individual agroforest trees to seperate tree effects into aboveground and underground factors.

Materials and Methods

Study Area

The study site was located on the western edge of the Willamette Valley in Corvallis, Oregon (44°33' N, 123°20' W). Soils are shallow, well-drained, silty-clay loams (Vertic Haploxerolls) of the Philomath series (Knezevich, 1975). This site is marginal for commercial timber production because of shallow soils and seasonally high water tables. The elevation is 60 m above mean sea level with a northeast aspect. Climate is Mediterranean maritime with warm dry summers and cool moist winters. Precipitation falls mainly as rain from November through March, totaling about 70% of the average 1,024 mm. Less than 100 mm of precipitation is received during the summer dry period from June to September. The frost-free period is 165-200 days (Knezevich, 1975).

Three 0.5 ha replications of pasture and silvopasture were plowed and planted with twenty kg/ha of rhizobium inoculated subterranean clover seed in fall 1989. Perennial ryegrass (*Lolium perenne* L.) from the residual soil seed bank slowly increased over time, presumably due to increasing soil nitrogen from N-fixation by subclover. Agroforest replications were planted with two-year-old (1-1) bare root Douglas-fir (*Pseudotsuga menziesii* L.) seedlings in winter 1988-89. Trees were planted in rows oriented with an azimuth of 60°, where 0° is true North and 90° is East. There

Table 2.1. Precipitation on the Research Site for 1992,1993,1994, and 30-year Average for Corvallis, Oregon. Measurements are given in centimeters.

	1992	1993	1994	30-Year Average
January	13.92	12.90	12.27	17.32
Febuary	13.84	5.82	16.43	12.80
March	2.97	14.33	9.63	11.56
April	12.85	20.17	6.12	6.50
May	0.15	14.07	4.47	4.95
June	1.83	6.55	5.03	3.12
July	2.51	2.72	0.10	1.32
August	0.56	0.94	0.00	2.21
September	3.45	0.10	2.36	3.84
October	10.90	2.67	16.18	7.90
November	16.00	4.27	23.93	17.32
December	22.12	22.66	15.19	19.61
Calendar Year Total	101.12	107.19	111.71	108.46
Forage Year Total (Feb-July)	34.163	63.6524	41.783	40.259

are 2.5 m between trees within rows and 7 m between tree rows. The trees are now large enough, many over 2 meters in height with canopy diameters of approximately 1 meter, to have observable influence upon forage production patterns and vary enough in size to allow comparisons between tree sizes (range of sample tree heights was 1.21 m to 3.77 m). Both pasture and agroforestry replicates were grazed by sheep two times during the growing season, once during early spring (late April-mid May) and again in late spring (mid-June through July) each year. Sufficient sheep were employed to remove approximately half of the forage present within 2-5 days. Trees were protected from livestock by portable electric fences placed parallel to tree rows, 0.5 m from tree stems.

Species Composition and Clipping Data

Herbage biomass estimates were made by clipping and drying understory forage in agroforest plantations and pastures. Clipping data was obtained during the early spring and mid-late spring growing seasons in 1993 and 1994. Before the sheep were allowed to graze, ten to twelve trees per replication were randomly selected as endpoints for clipping transects. All plant material within six 0.10 m^2 plots ($0.25 \text{ m} \times 0.40 \text{ m}$ rectangles) per transect was clipped to ground level. Transects plots were placed every 0.5 m beginning 1 m from the sample tree and extending to the middle of the row. Transects were established perpendicular to the tree row in both northern and southern orientations. Five transects per pasture replication were clipped on a similar spacing, starting 0.5 m from the electric perimeter fences. All clipped samples were oven-dried and their weights were recorded.

Forage species composition based upon plant canopy cover was determined just prior to grazing in early May each year. Point contacts were recorded using twenty randomly placed, 10-point frames (Sharrow and Tober, 1979) for a total of two hundred points for each plot.

Table 2.2. Percent Species Composition (Proportion of Cover) of Pastures and Agroforests in Spring 1993.

	1993	Standard	1993	Standard
	Pastures	Error	Agroforests	Error
Subterranean clover (*Trifolium subterraneum* L.)	42.89	1.67	38.13	1.39
Other Legumes (Nitrogen-fixers)	2.68	0.33	4.52	1.27
Garden burnet (*Sanguisorba minor* Scop.)	5.05	5.05	5.36	5.36
Other Forbs (Dicots)	9.72	0.74	9.53	1.25
Annual grasses	8.55	0.61	11.37	0.16
Perennial ryegrass (*Lolium perenne* L.)	21.23	8.15	22.40	4.21
Meadow foxtail (*Alopecurus pratensis* L.)	4.35	2.98	2.00	1.32
Tall oatgrass (*Arrhenatherum elatius* L. J.S. Presl & C. Presl)	5.04	2.60	4.68	2.35
Other Perennial grasses	0.51	0.51	2.01	0.29
Bare Ground	0.50	0.29	0.33	0.17

Table 2.3. Percent Species Composition (Proportion of Cover) of Pastures and Agroforests in Spring 1994.

	1994	Standard	1994	Standard
	Pastures	Error	Agroforests	Error
Subterranean clover (*Trifolium subterraneum* L.)	6.34	5.02	4.29	1.94
Other Legumes (Nitrogen-fixers)	2.77	0.84	2.76	1.11
Garden burnet (*Sanguisorba minor* Scop.)	9.24	9.24	8.43	8.43
Other Forbs (Dicots)	10.77	2.37	21.59	3.40
Annual grasses	28.03	3.86	31.07	5.13
Perennial ryegrass (*Lolium perenne* L.)	12.82	5.37	8.29	4.36
Meadow foxtail (*Alopecurus pratensis* L.)	17.90	10.06	4.68	3.90
Tall oatgrass (*Arrhenatherum elatius* L. J.S. Presl & C. Presl)	4.31	3.58	2.71	1.41
Other Perennial grasses	7.81	2.04	16.18	6.39
Bare Ground	4.83	1.74	9.83	2.59

Photosynthetically Active Radiation (PAR)

Measurements of photosynthetically active radiation (μmols s^{-1} m^{-2}) were obtained using LI-COR quantum sensors. The spectral bands sampled (LI-COR, 1986) ranged from 0.40 μm (blue) to 0.70 μm (red). Six sensors were arranged in an array, one every 0.5 m, along a PVC pipe. The pipe was supported 0.3 m above the ground by a plywood datalogger enclosure. By this means, the sensors were positioned above the understory vegetative canopy while recording measurements, which corresponded to transect clipping plots from 1.0 m to 3.5 m from trees. Sensors were attached to a LI-COR LI-1000 datalogger which recorded measurements every 30 minutes from all six sensors. Two PAR arrays allowed simultaneous data collection on opposite sides of a tree. A minimum threshold of 10 μmols s^{-1} m^{-2} was set to exclude nighttime readings. Comparative open sun readings were recorded using a single PAR sensor and datalogger placed in the middle of an open pasture. A series of PAR readings were obtained starting June 1994 and ending September 1995 from four randomly selected trees. Sensor arrays were moved at randomly selected times to sample for the general effects of tree size, slope of site, and aspect of site as part of a longer term study on PAR availability.

Modeling of Shadows

The availability of solar energy on a site is dependent upon latitude, season, and weather patterns. The first two variables can be used to predict available solar energy for a site at a specific time, adjusted for the effect of weather (Leckie et al., 1981). Modeling of shadows was accomplished using the following equations. The angle of the sun in relation to the equatorial plane is called the solar declination, δ, and can be calculated for any day of the year using the following relationship:

$$\delta = 23.45 \, sin \, [360 \times (284 + N)/365]$$

Table 2.4. Comparison of Mathematical Modeling of Shadow Length of Neighbor Tree with Average PAR Reading for South Transect. PAR measurements are average readings recorded for the 30-minute interval. Units are μmols s^{-1} m^{-2}.

Obs. period	Solar Altitude degrees	Local Time	Neigh. Tree Ht.(cm)	Predict. Shadow in m	PAR 1.0 m South	PAR 1.5 m South	PAR 2.0 m South	PAR 2.5 m South	PAR 3.0 m South	PAR 3.5 m South	PAR of Full Sun
Mar 10 Mar 22[1]	38.20	10:39 AM	267	3.39	561.45	558.24	561.89	623.23	638.89	609.35	580
Apr 2 Apr12[1]	51.26	11:53 AM	267	2.14	803.34	797.44	791.02	712.46	812.00	739.90	780
May 22 May 30[1]	61.37	12:07 PM	267	1.46	1792.25	1757.38	1849.88	1783.88	1798.88	1769.63	1780
Jun 14 Jun 27[2]	66.46	12:19 PM	224	0.98	1147.36	1240.21	1155.53	1227.93	1239.52	1232.69	1250
Sept 19 Sept 22[1]	43.58	11:40 AM	329	3.46	1252.67	1277.67	1327.00	1371.33	1278.33	1247.00	1260

[1] data collected 1995   [2] data collected 1994

where N is the Julian day, N = 1 is January 1 and N = 365 is December 31. The apparent daily solar path is described using two component angles, an altitude angle, α, and an azimuth angle, a_s. The altitude angle at solar noon, α_N, is obtained for a site from the formula:

$$\alpha_N = 90° - L + \delta$$

where L =Latitude, 44°33' or 44.62° for our site. The sun's altitude angle can then be calculated for any time of the day using the relationship:

$$sin\ \alpha = cos\ L\ cos\ \delta\ cos\ h + sin\ L\ sin\ \delta$$

where h is called the hour angle and is equal to 15° for each hour away from solar noon. The azimuth angle at any time is given by the relationship:

$$sin\ a_s = (cos\ L\ sin\ h)\ /\ cos\ \alpha$$

(ASHRAE 1991). Using the above formulas, we calculated the solar altitude for a solar azimuth of 150°. This is the orientation for our agroforestry plots where the tree is directly in line between the sun and the north PAR sensor array. In this position, the tree casts its shadow directly down the sensor array. Using the solar altitude angle and the tree's height, we can then calculate the length of the shadow cast on level ground with the formula:

Length of shadow = Square Root of (((tree height/$sin\ \alpha$)^2-(tree height)^2)

Data Analysis

Available solar energy differences between and within arrays of sensors (distance and direction from tree), and differences between arrays and an open-sky (pasture) sensor were examined using analysis of variance (ANOVA) with individual observation days within periods as replications. The ANOVA model was a split-block in time with array placement (to the north or south of tree) as treatments and with the pasture as a control. Treatments and control served as main plots, sensor position (distance from tree) as subplots, and sampling times as sub-subplots. Means for significant treatment effects were separated using a Least Significant Difference (LSD) procedure at $p<0.10$ (Chao, 1974).

The pattern of solar energy available around individual trees was quantified by fitting least square regression surfaces to PAR data. Regression equations with the highest R^2 and lowest standard error were selected as best fit surfaces (Draper and Smith, 1981). Regression analysis using linear, multiplicative, reciprocal, and exponential formulas showed that linear formulas produced higher R^2 values and reduced the complexity of interpretations. Spatial pattern of forage production north of trees was compared to that south of trees by comparing their best fit regression models using a test for homogeneity of regression coefficients (Steel and Torrie 1980). Independent variables used in the modeling were: observed tree height, observed tree trunk and canopy diameter, heights and trunk diameters of five neighboring trees, sensor distance from observed tree, length of day during collection period, maximum solar angle, aspect and slope of PAR arrays, and all possible combinations of the above.

Forage production differences between transect positions and treatments were examined by ANOVA using blocks as replications. The ANOVA model was a split block in time with treatments as main plots, transect position as subplots, years as sub-subplots, and sampling dates as sub-sub-subplots. Means for significant treatment differences were separated using LSD procedure at $p>0.10$ (Chao, 1974). The basic

pattern for forage production around individual trees was analyzed by graphing clipping data using the plot's position relative to tree or fence for the x-axis to simplify visual recognition of treatment patterns. Patterns were classed as isotropic or anisotropic based on similarities or differences between transect patterns and mean separations (LSD) of treatments (Isaaks and Srivastava, 1989).

Results and Discussion

Comparisons of predicted shadows with PAR data show good agreement in timing of shadows, shading patterns, and length of shadows (Table 2.4 and Table 2.5). Variation in local skylight conditions, haze or clouds, are apparent in the readings. Both shadow predictions and PAR data suggests that trees have little effect upon incoming solar radiation on their south side, except for directly under the tree canopy (Table 2.4). Cumulative daily PAR obtained from the open pasture sensor and those of transect sensors 3.0 m and 3.5 m from either side of the tree were not different (P>.10). Trees consistently reduced average PAR reaching forage plants within 1 m of trees to the north side (Table 2.5). The range of values varied seasonally from 35% of full sun in April to 18% of full sun in August.

It should be noted that the PAR readings for September 1995 were taken from a much larger tree, 416 cm, than the other readings where the tree heights averaged 265 cm. The shadow from the larger tree decreased light intensity levels more than a smaller tree because of the greater density and width of the tree canopy and affected positions farther away from the tree because of greater tree height. This is the effect we see based on calculated shadow lengths as well as in the PAR data. One meter north of the tree, available solar energy is 14% of full sun, while 3.5 m north of the tree solar energy only reaches 37% of full sun. While these levels are above the light compensatory level for the understory plants, they are below the light saturation level (Salisbury and Ross, 1992, and Harper, 1977) suggesting that the reduction in available

Table 2.5. Comparison of Mathematical Modeling of Shadow Length of Observation Tree with Average PAR Reading for North Transect. PAR measurements are average reading recorded for 30-minute interval. Units are μmols s^{-1} m^{-2}.

Obs. period	Solar Altitude degrees	Local Time	Tree Height in cm	Predict. Shadow in m	PAR 1.0 m North	PAR 1.5 m North	PAR 2.0 m North	PAR 2.5 m North	PAR 3.0 m North	PAR 3.5 m North	PAR of Full Sun
Feb 22 Mar 5[1]	31.79	10:34 AM	282	4.55	190.09	239.97	239.97	565.98	718.47	668.25	870
Apr 26 May 5[1]	57.05	12:01 PM	282	1.83	299.30	755.02	848.00	796.06	865.07	878.66	860
May 17 May 22[1]	62.52	12:16 PM	282	1.47	369.35	1211.89	1455.66	1349.29	1504.59	1511.14	1500
Jun 14 Jun 27[2]	66.41	12:19 PM	268	1.17	369.65	1161.45	1199.02	1334.78	1259.71	1253.22	1250
Jul 10 Jul 18[2]	64.52	12:18 PM	249	1.19	864.14	1586.57	1500.71	1637.29	1533.71	1543.86	1540
Aug 9 Aug 17[2]	56.70	12:05 PM	249	1.64	201.69	546.79	1038.51	1223.19	1160.73	1175.64	1150
Sept 24 Oct 4[1]	37.59	11:28 AM	416	5.40	159.98	235.55	*	190.20	357.85	430.57	1170

* datalogger failure   [1] data collected 1995   [2] data collected 1994

Table 2.6. North Regression Model for Daily Cumulative PAR.

Model-fitting Results for Daily Cumulative PAR (μmols s^{-1} m^{-2}) from North (330°azimuth) array.

Independent Variable	Coefficient	Standard Error	Range of Values
Constant	-48143.08	6137.36	-59310.50 to -37370.80
Length of Day hours	2869.43	208.24	2543.82 to 3269.11
Slope of array percent	2415.14	389.25	1763.45 to 3123.22
Aspect of array degrees azimuth	75.78	11.41	55.05 to 94.92
Tree height/dist. cm/m	-38.63	7.55	-53.31 to -27.04

Adjusted R^2 = 0.83   Standard Error = 3914.96

47 Observations fitted, one forecast fitted for missing value of dependent variable

Table 2.7. South Regression Model for Daily Cumulative PAR.

Model-fitting Results for Daily Cumulative PAR (μmols s^{-1} m^{-2}) from South (150° azimuth) array.

Independent Variable	Coefficient	Standard Error	Range of Values
Constant	-60176.57	4947.04	-70931.00 to -51857.30
Length of Day hours	3128.88	181.27	2743.14 to 3395.26
Slope of array percent	2839.45	307.17	-3191.90 to 5937.48
Aspect of array degrees azimuth	86.83	8.87	55.87 to 83.22

Adjusted R^2 = 0.85   Standard Error = 3112.25

59 Observations fitted

solar energy might decrease biomass production at this stage of tree growth. The data for September, while not representing part of the main growing season, is important because germination and establishment of subterranean clover occurs at this time. Patterns for September are also indicative of those for March when the same solar path is traced by the sun. We can use these data to help predict the effects of tree growth on shadow patterns and lengths. For this agroforestry design, when trees reach eighteen meters in height, they will cast a shadow across the entire alleyway on the summer solstice, June 21, towards the end of the forage growth season. This stage of growth is close to the 20 to 30 percent tree cover mentioned by Krueger (1981) as showing noticeable reductions in forage production.

As one might expect, PAR patterns around trees were strongly anisotropic with shadows being cast predominately on the north side of trees. Stepwise regression modeling of the combined transect PAR data did not produce a single suitable model (adjusted $R^2<0.18$). However, R^2 values for seperate north and south transect models ranged from 0.83 to 0.85 for both daily cumulative PAR (Table 2.6 and Table 2.7) and daily average PAR (Table 2.8 and 2.9). Daily average PAR models contained fewer variables, were simpler to define, and had approximately the same R^2 values as cumulative PAR models so we will use them in our discussion. PAR reaching the forage canopy varied with "length of day" in both north and south transects. The variable "length of day" has a universal effect as it occurred in all average PAR and cumulative PAR models. This variable can be thought of as representing general seasonal effects as it reflects not only the longer hours of daylight as one moves towards the solstice, but also the accompanying greater solar angles and higher light intensity levels evident in the PAR data (ASHRAE, 1991). The tree related variable in only north side models indicates that the tree shadow affects available PAR energy to the north of the tree only or displays an anisotropic pattern. The ratio of tree height/distance from the tree was used to represent tree effects and to account for the interrelationship between tree size and the length of its shadow. The addition of this variable to the north model substantially increased adjusted R^2 values from 0.39 to 0.84.

Table 2.8. North Regression Model for Daily Average PAR.

Model-fitting Results for Daily Average PAR (μmols s^{-1} m^{-2}) from
North (330° azimuth) array.

Independent Variable	Coefficient	Standard Error	Range of Values
Constant	-373.49	93.26	-561.50 to -185.50
Length of Day hours	83.69	6.05	71.50 to 95.88
Tree height/dist. cm/m	-1.45	0.23	-1.91 to -0.98

Adjusted R^2 = 0.84   Standard Error = 119.68

47 Observations (periods) fitted, one forecast fitted for missing value of dependent variable

Table 2.9. South Regression Model for Daily Average PAR.

Model-fitting Results for Daily Average PAR (μmols s^{-1} m^{-2}) from
South (150° azimuth) array.

Independent Variable	Coefficient	Standard Error	Range of Values
Constant	-615.47	76.69	-743.72 to -487.22
Length of Day hours	92.20	5.47	83.08 to 101.33

Adjusted R^2 = 0.83   Standard Error = 100.92

59 Observations fitted

In general, north transect PAR readings increased rapidly with distance from trees within the first 1 to 1.5 m, then stabilized at open pasture levels for distances greater than 2 m (Table 2.10). Position south of trees had relatively little effect upon measured PAR. Transect positions south of the tree were within 9 percent of each other with the position three-and-a-half meters from the tree receiving the lowest amount of energy, suggesting neighboring tree shadows extended across row middles. However, these differences were not statistically significant from each other or open pasture levels (p<0.10). In the context of physiological response, the PAR levels at all positions are at or above the light saturation level (approximately 50% of full daylight) for the understory plants (Salisbury and Ross, 1992, and Harper, 1977), and we would expect little reduction in growth from reduced light levels. As trees grow in height, their influence on incoming solar radiation extends farther from the trunk. Such an effect is predicted by shadow modeling and is evident in PAR data for the southern transect in which the shadow from a large tree in an adjacent row appears to have reached the center of the alley between rows. Therefore, we would expect tree growth to have a greater impact on available solar energy in the future possibly altering the relationship of underground factors to aboveground factors in determining pasture growth.

During the years of 1993 and 1994, we were fortunate to experience an above-average rainfall year and a more typical average rainfall year, respectively (Table 2.1). Plant responses can be quite different when the relative importance of a primary resource, such as water, shifts substantially as in this case. Herbaceous plant composition varied between the two years, reflecting differences in the monthly amount and seasonal pattern of precipitation each year. The understory cover in 1993 (Table 2.2) was dominated by subclover (38 percent) with a substantial perennial ryegrass component (22 percent). Germination and establishment of subclover is dependent upon adequate rainfall in the fall (Raguse et al., 1994, and Lanini et al., 1995). September and October of 1992 were average and above-average rainfall months, respectively (Table 2.1), which helped subclover establishment. Rainfall during the growing season started below normal during the month of February but exceeded the

Table 2.10. Average Daily Total of Photosynthetically Active Radiation (PAR) for Time Periods Relating to Growing Seasons Preceding Clipping.

Distance from tree	1st Growing[1] Per. North	1st Growing[1] Per. South	2nd Growing[2] Per. North	2nd Growing[2] Per. South
(m)	Percent Full Sun	Percent Full Sun	Percent Full Sun	Percent Full Sun
1.0	49*	100	56*	100
1.5	78*	99	91	100
2.0	92	97	100	99
2.5	96	93	100	100
3.0	100	100	99	100
3.5	100	91	100	96

1st Growing[1] Period is February 1st through May 15th.
2nd Growing[2] Period is May 15th through June 30th.

* means within columns vary $p<0.10$.

30-year average for March-July. Average forage yield of agroforest transect plots (Figure 2.1) did not differ (p<0.10) from open pasture yields in late May. Distance from trees had no apparent effect upon agroforest herbage yield (p<0.10). However, herbage yield in late June followed a distinctly isotropic pattern. Forage production was numerically highest 2.5 m from both north and south sides of the trees. Forage production within 2 meters of a tree, north or south, was lower than open pasture levels (p<0.10), suggesting that isotropic competition was occurring. This pattern suggests that underground factors dominated competition even during periods of abundant moisture, possibly through a limitation of available nutrients as well as available moisture (Tisdale et al., 1985). June forage production in the center of alleys, at 3 and 3.5 m from trees, was well below open pasture values. Remote sensing analysis of large-scale aerial photos taken of the research area (Harris et al., 1996) clearly delineated pathways in alley centers created by sheep and indigenous deer in response to the electric fence protecting trees from browse damage. A similar pattern of reduced forage production and utilization near electric fences was evident at the edge of pastures. This pattern of low production in alley centers was not noted in the study by Yunusa et al. (1995b) who used mowed plots instead of grazing. Overall forage production for agroforest plots was 87 per cent of pasture production (Table 2.11). Positions near trees and in row middles showed the largest differences. Standard errors for agroforest plots were twice those of pasture plots, indicating more variation in agroforest production patterns.

The understory vegetation of agroforests in 1994 (Table 2.3) was dominated by non-leguminous forbs (31 percent), and perennial and annual grasses (37 percent), while subclover contributed less than 5 percent. This shift in forage composition can be traced to droughty fall conditions when rainfall for September through November of 1993 (Table 2.1) was considerably below the 30-year average. A similar shift was shown in pasture composition with non-leguminous forbs at 28 percent, perennial and annual grasses at 36 percent, and subclover at 6.34 percent. The precipitation pattern in 1994 was the reverse of that seen in 1993. Precipitation in February 1994 was above

Figure 2.1. 1993 Understory Production.
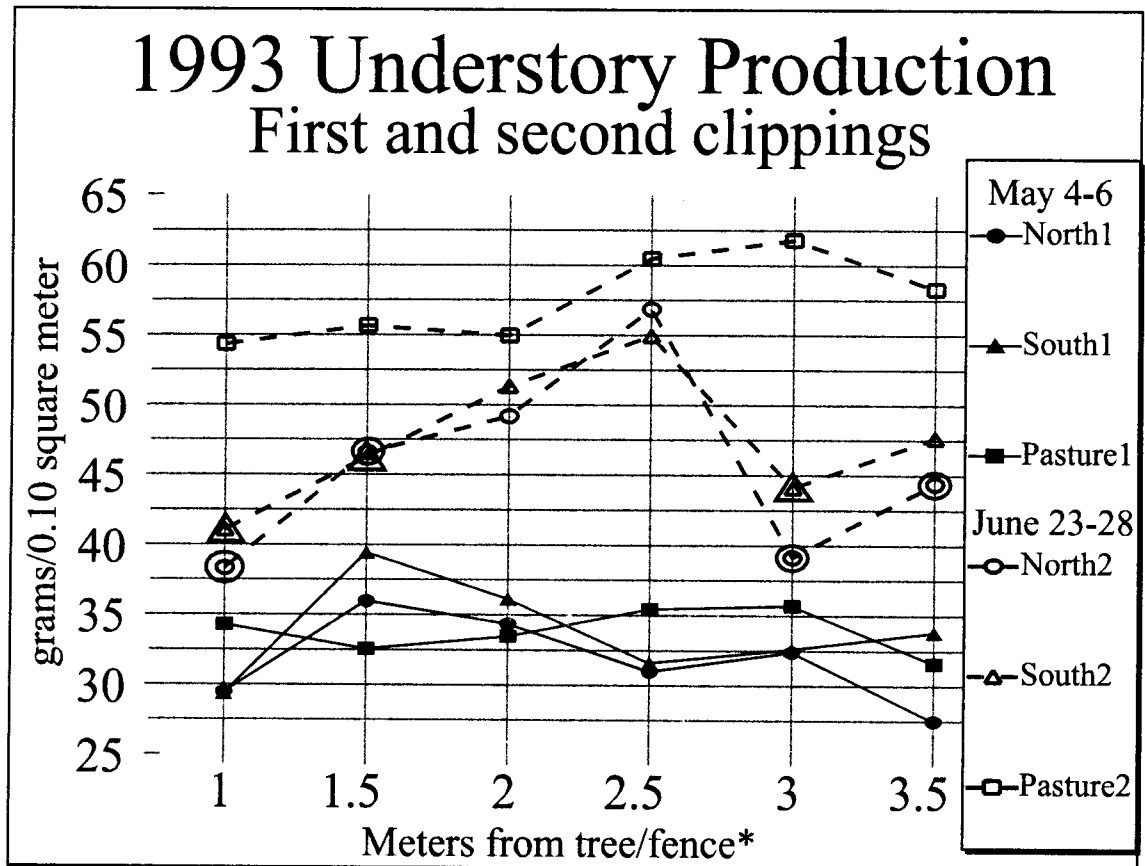
Measurements are given in dry weight biomass.

1993 Understory Production
First and second clippings

Doubled symbols indicate that transect weights are significantly different (p=0.10) from the same clipping period pasture weight at that position.

*Pasture measurements are taken starting 0.5m beyond the electric fence to correspond to tree trunk position in relationship to temporary fence.

average, while March through July totals were average or below average. Tree effects upon understory plant production (Figure 2.2) appeared to be strongly isotropic for the period before mid-May. Forage yield within agroforest alleys was similarly reduced relative to open pasture regardless of its position either north or south of trees, again suggesting a dominance by underground factors. An anisotropic pattern of herbage production within agroforests began to emerge during June as available soil moisture declined and air temperatures rose. Reductions in forage production were most pronounced on the south side of the trees within 2 meters, suggesting that shade may have provided a compensatory factor which offset water competition on the north side of trees. While the south transect was significantly different from pasture production at these positions, the differences between agroforestry transects were not statistically significant (p>.10). Shade near trees might maintained a climatic condition, probably reduced temperatures and evapo/transpiration requirements, that is facilitative for biomass production on the north side compared to the south side. Shading and decreased light levels are known to increase production in certain cases, especially drought (Everett et al., 1983, Helms, 1963, and Wilson et al., 1986). Averaged across all transect positions, agroforest production was 87 and 78 percent of pasture production (Table 2.11 and Table 2.12) in 1993 and 1994, respectively. Production was depressed all the way across agroforest alleys compared to pasture plots.

Detailed examination of forage production patterns suggests there are often several forces acting concurrently to produce these patterns. The magnitude with which these forces express themselves varies considerably depending on complex natural interactions (Harper, 1977). Spatial pattern analysis revealed predominately isotropic patterns of herbage yield in 1993 and 1994, which were more pronounced in the second, warmer and drier, half of the forage production season. Anisotropic patterns were evident near trees in the second half of the 1994 growing season but were relatively small compared to isotropic effects. While the pattern suggests a strong isotropic dominance, it is likely that two or more isotropic forces are reflected in it. If we accept that the differences at alley middles are caused by animal use patterns, the remaining

Table 2.11. Comparison of Forage Production between Agroforests and Pastures for 1993.

Measurements are given as average dry weight biomass in kg/ha.

Distance from Tree/Fence (m)	Combined Agroforest Transects	Standard Error	Pastures	Standard Error
1	6913	2296	8866	1211
1.5	8414	2681	8824	1327
2	8550	2903	8843	1250
2.5	8721	3229	9590	1478
3	7416	2417	9748	1533
3.5	7669	2663	8990	1516
Transect Average	7947	2698	9143	1386

Table 2.12. Comparison of Forage Production between Agroforests and Pastures for 1994.

Measurements are given as average dry weight biomass in kg/ha.

| Distance from Tree/Fence (m)	Combined Agroforest Transects	Standard Error	Pasture	Standard Error
1	4249	1095	5485	736
1.5	4578	1192	5471	672
2	4388	1159	5966	599
2.5	4325	1103	5512	475
3	4229	1020	5693	678
3.5	4361	1254	5348	528
Transect Average	4355	1137	5579	615

isotropic pattern closely approximates the neutron probe soil moisture data of Yunusa et al. (1995a) for a subclover/ryegrass understory suggesting soil moisture levels combined with animal use are the forces that control biomass production in our agroforests.

Conclusions

Patterns of forage production associated with trees contain both isotropic and anisotropic components that can be used to understand the underlaying ecosystem processes that produce them. Distribution of solar energy (PAR) about trees was predictable by mathematical shadow modeling. Shade was strongly anisotropic in nature, differing markedly between the north and south sides of trees. On the other hand, competition between trees and understory vegetation in our young agroforests was predominately isotropic in nature. This suggests that young trees affect understory herbage production more through competition for soil resources rather than light. The linear structure of our agroforest tended to concentrate ungulate use into the centers of alleys between trees, which appeared to decrease forage production in the alley centers. Interactions between woody vegetation patterns and grazing animal behavior in agroforests are largely undocumented. Our data suggest that this is an area of considerable interest for silvopasture design. Reduced light (an anisotropic factor) appeared to play little role in tree/forage relations outside of the dense shade directly under the center of the tree canopy. In one instance, however, shade appeared to slightly increase understory production, presumably by reducing transpirational stress during hot dry periods. Based on these observations, it appears that agroforest manipulations that seek to manage shade effects on understory herbaceous vegetation in open canopy silvopastures will have limited effects compared to those that manipulate tree water and nutrient use.

Figure 2.2. 1994 Understory Production
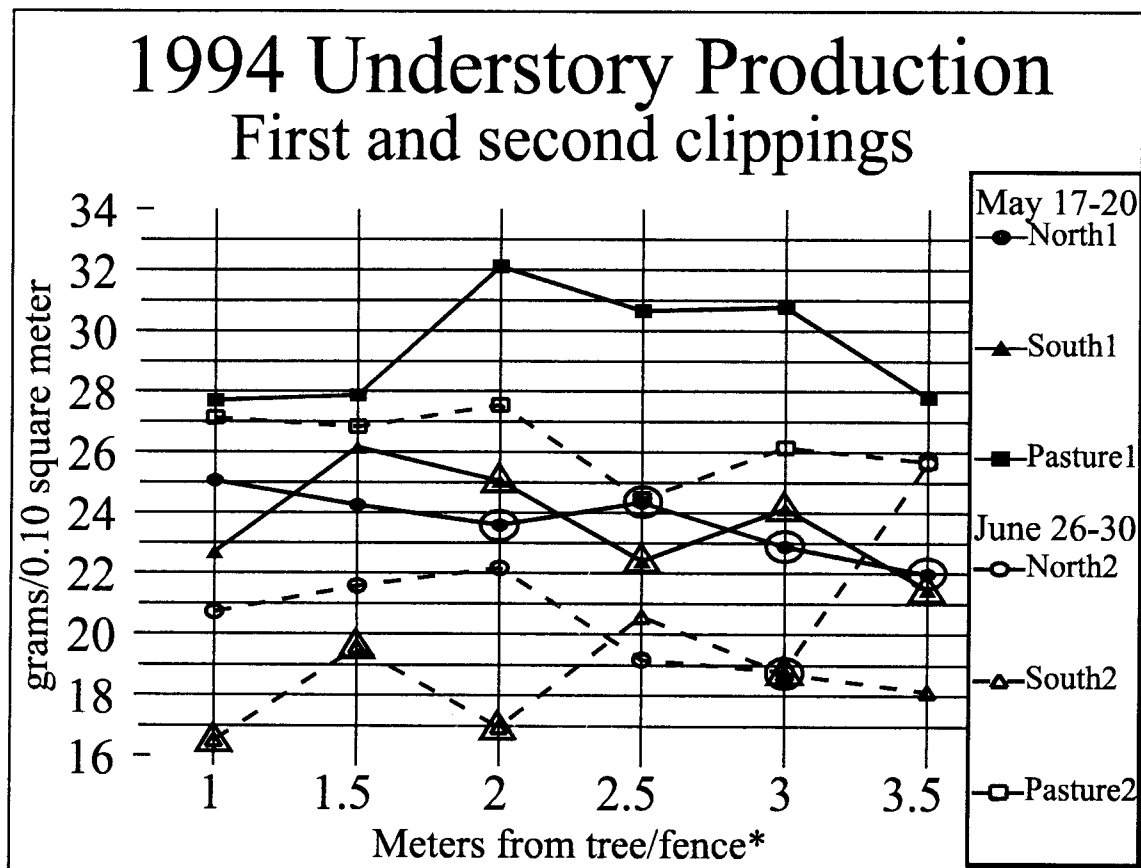
Measurements are given in dry weight biomass.

1994 Understory Production
First and second clippings

Doubled symbols indicate that transect weights are significantly different (p=0.10) from the same clipping period pasture weight at that position.

*Pasture measurements are taken starting 0.5m beyond the electric fence to correspond to tree trunk position in relationship to temporary fence.

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Chapter 3

Use of Low-Level Remote Sensing to Understand Tree/Forage Interactions in
Agroforests

Norman R. Harris, Steven H. Sharrow, and Douglas E. Johnson

<u>Abstract</u>

Low-level remote sensing using a small tethered blimp and two 35 mm cameras adds a new dimension to landscape analysis. The distance from the sensor to the object under investigation is less than 150 m, which makes possible the collection of high-resolution spatial data over blue as well as red, green, and infrared wavelengths. The relatively short atmospheric pathway causes less atmospheric scattering of the blue band, thereby increasing the utility of its data. Three blue/infrared and one red/infrared band-ratio vegetative indices were used to model dry weight production of pasture forage plants growing in association with conifer trees in three agroforests. Normalized Difference Vegetation Indices (NDVI) based upon the blue band were better predictors of pasture production than those based upon the red band in 2 out of 3 agroforests examined. No one model fit all three replications well. However, individual best-fit models developed for each agroforest predicted forage yields within 135 kg/ha (5.0, 5.8, and 8.9%) of actual harvested plots.

<u>Introduction</u>

Agroforestry is the joint production of trees with agricultural crops and/or animals. Agroforestry draws upon agronomic, forestry, horticultural, and animal science knowledge but differs from these fields by placing emphasis upon the interactions among agroecosystem components. Agroforesters group systems based upon their structural components into agrosilviculture (trees + crops), silvopastoral (trees + livestock), and agrosilvopastoral (trees + crops + livestock) systems (Nair, 1985). Of these three types, agrosilvopastoral systems are the most complex, both in their structure and management.

Strong conifer forest, forage crop, and livestock industries exist in both the western and southeastern United States. Integration of livestock and forest enterprises

with forage crops grown as improved pastures is the most commonly encountered agroforestry system in North America. Livestock in these systems are often sheep or cattle. Ground vegetation is generally a combination of pasture grasses and legumes that fill the available spaces underneath and between trees. This plant population provides food for the livestock, protects soil from erosion, and facilitates tree growth by fixing atmospheric nitrogen. However, uncontrolled pasture growth may compete with young trees for soil moisture and provides a habitat for small mammals that gnaw on trees. Livestock harvest forage, control competition between trees and forage, reduce invasion by weedy plants, and recycle forage nutrients as dung and urine.

This complex set of biological interactions among agroforest components is reflected in an equally complex spatial structure. Trees are a fundamental element of agroforest structure. Livestock grazing patterns as well as pasture production may be affected by the proximity of trees.

Many studies have been conducted on the relationship between tree basal area, or cover, and understory production. Sharrow (1991) reported that 10-year-old conifer trees have a detrimental effect on forage production for a distance approximating 2 canopy diameters with no effect apparent beyond that distance. Other work (Woods et al., 1982, Cameron et al., 1991, and Joyce and Mitchell, 1989) has shown a similar pattern of detrimental effects, which lessen with increasing distance from the tree. The exact response of a plant to these effects varies by tree and forage species. Arnold (1964) observed distinct compositional zones of native forage plants around juniper trees, which suggests differing responses among species to the presence of the tree with some species increasing while others decrease. Pieper (1990) found that production of cool season grasses increased under the canopy of pinyon-juniper trees while that of warm season grasses declined. A similar effect was predicted by a model developed by Scanlon (1992) which used factors relating to both beneficial and detrimental responses to predict forage production in reference to distances from trees.

Both beneficial and competitive effects accrue from the interactions between plants as they attempt to use the resources available to them. Site resources for which competition might occur include quantity and quality of light, soil moisture, and soil nutrients. Nutrient uptake and water uptake are interdependent processes, so a more functional division might be the aboveground (light) factor or the belowground (moisture and nutrients) factor. Work by Young and Smith (1982 and 1983) showed that light or water could be the most limiting factor depending on the environmental factors during the year. Riegel (1989) found underground factors to be the most important in the forest systems of northwestern Oregon. Within the belowground factor, soil nutrients are likely the most important factor during spring, while soil moisture dominates plant interactions during dry periods such as summer or during droughts (Krueger, 1981, and Riegel, 1989). Karl and Doescher (1993) also found water relations to be the most important in the open canopied forests of southwest Oregon. Agroforesters manage agroecosystem processes primarily through manipulating system spatial structure. Successful agrosilvopastoral design and management relies upon a fundamental understanding of how spatial structure relates to agroecosystem processes of competition, succession, nutrient cycling, carbon flow, and hydrology. Our study attempts to use low-level remote sensing technology to identify and quantify tree and site spatial variables that exert major influences on pasture growth. It is hoped that description of spatial vegetation and environmental patterns will suggest the nature and intensity of the interactions between agroforest components as they share resources in time and space.

Remote sensing is the science and art of gathering information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand and Keifer, 1987). Accurate analysis of remotely sensed plant community data is dependent on an understanding of the reflectance/absorbance of energy from vegetation. Energy in the near infrared range (0.70μm to 1.30 μm) is reflected strongly with values reaching 50 percent of incident radiation (Knipling, 1970). The reflectance of infrared is related to

the structural complexity of vegetation biomass (Grant, 1987). This complexity varies considerably between species with dicots reflecting greater amounts of infrared than monocots (Salisbury and Ross, 1992). These structurally caused reflective differences between species form the basis of most classification procedures (Chen et al., 1995, and Knipling, 1970). Visible light (0.40 μm to 0.70 μm), composed of the primary colors, red, green, and blue, is reflected weakly by vegetation with reflectance values ranging from 5 to 20 percent of incident radiation. Energy in the blue and the red ranges is absorb by plant chlorophyll and is used to power photosynthesis (Salisbury and Ross, 1992). Therefore, dense, high chlorophyll-content vegetation will absorb more red and blue energy and reflect less than sparse or low chlorophyll-content vegetation. Where the understory is of a homogeneous composition (ie. agronomic forage crops and pastures) differences in reflectance form a gradient indicating increasing biomass. Certain plant species reflect noticeably more blue light than others and appear as a blue-green color. Because of these species-related differences, the blue band contains more information for some vegetation types than does the red band. Tucker (1977), for instance, noted that wet or dry weight biomass had its strongest correlation with the blue band (0.35 μm to 0.44 μm). However, most vegetation indices are based on near-infrared/red band ratioing (Richardson and Everitt, 1992). Atmospheric *Rayleigh* scatter, which causes the blue color of the sky, makes blue light hard to accurately detect and measure. The longer the atmospheric pathway between object and sensor, the more severely the blue channel is distorted by scatter. Past emphasis on satellite and high-altitude aerial photography has rendered blue band data relatively unimportant. So much so, that many satellite systems, such as the SPOT, have abandoned blue band detection entirely (Lillesand and Keifer, 1987). However, when the sensor is located less than 150 meters from the target, the potential usefulness of blue band data increases considerably.

Our study investigates the utility of very low-level overflight photographic data to predict and to interpret the effects of agroforest trees upon associated pasture forage production. This paper focuses on the detection of spectral data using a small tethered

blimp and two 35 mm cameras and the importance of blue band data in modeling herbaceous plant dry weight biomass.

Materials and Methods

Study Area

The study site was located on the western edge of the Willamette Valley near Corvallis, Oregon (UTM Zone 10n, 476050 E 4933900 N). Soils are shallow, silty-clay loams (Vertic Haploxerolls) of the Philomath series. Although conifer trees grow naturally on the site, it is marginal for commercial timber production because of shallow soils and seasonally high water tables. The elevation is 60 m above mean sea level with a northeast aspect. Climate is maritime with warm dry summers and cold moist winters. Precipitation falls mainly as rain from November through March, contributing about 70% of the annual average 1,024 mm. Less than 100 mm of precipitation is received during the summer dry period from June to September. The frost-free period is 165-200 days. Areas abutting the site are a combination of oak savanna and urban housing developments.

Three 0.5 ha agroforest replications were planted with two-year-old (1-1) bare root Douglas-fir (*Pseudotsuga menziesii*) seedlings in 1989. Trees were planted in rows running approximately west-east with 2.5 m between trees within rows and 7 m between rows. The trees are now large enough, some over 2 meters in height, to have observable influence upon forage production patterns and vary enough in size to allow comparisons between tree size classes.

Twenty kg/ha of rhizobium inoculated subterranean clover (*Trifolium subterraneum L.*) seed was planted in 1989. Perennial ryegrass (*Lolium perenne L.*) from the residual soil seed bank slowly increased over time, presumably due to

Figure 3.1. Species Composition of Agroforestry Plots for 1994.
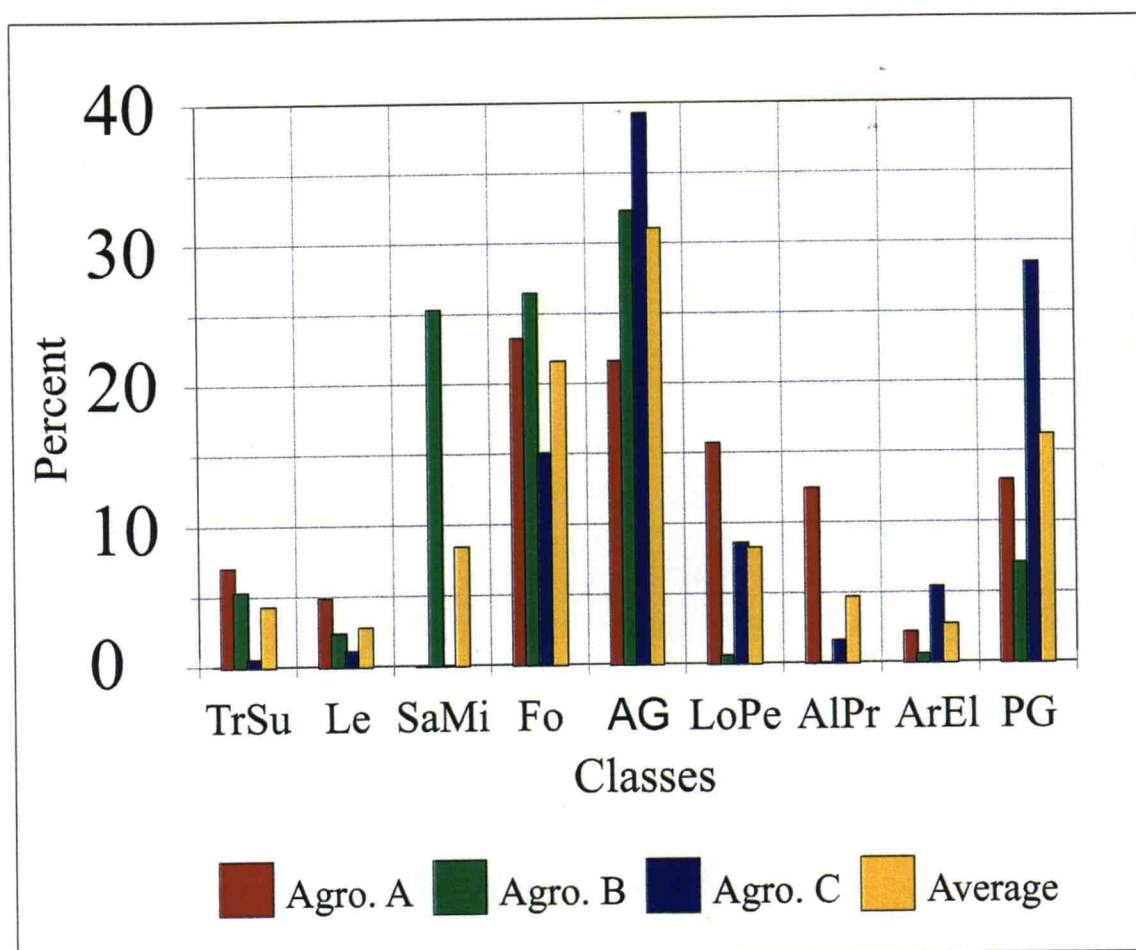
Abbreviations of plant names are as follows: TrSu = subterranean clover (*Trifolium subterraneum* L.), Le = other legumes (nitrogen fixers), SaMi = garden burnet (*Sanguisorba minor* Scop.), Fo = other forbs (dicots), AG = other annual grasses, LoPe = perennial ryegrass (*Lolium perenne* L.), AlPr = meadow foxtail (*Alopecurus pratensis* L.), ArEl = tall oatgrass (*Arrhenatherum elatius* (L.) J.S. Presl & C. Presl), PG = other perennial grasses.

increasing soil nitrogen from N-fixation by subclover. Average understory composition is usually 40 percent subterranean clover, and 28 percent perennial ryegrass, with annual grasses and miscellaneous broadleaf plants making up the remainder. However, in 1994 of subterranean clover was considerably reduced by drought. Understory composition in 1994 was about 55 percent annual grasses and broadleaf plants with another 25 percent perennial grasses (Figure 3.1). Forage species composition was noticeably different in Agroforest B, where total herbage production was relatively low and contained about 17 percent burnet (*Sanguisorba minor Scop.*).

Ground Data Collection

Species composition for each agroforest was determined at the end of May 1994. Point contacts were recorded using twenty random, 10-point frame sets (Sharrow and Tober, 1979) for a total of two hundred points for each agroforestry replicate. After the aerial photos are taken and before the sheep were allowed to graze, twelve random trees per replication were selected as endpoints for clipping transects. Seven 0.1 m^2 plots (25 cm X 40 cm rectangles) were clipped for each transect starting at a point 0.5 m from the tree. Transects were established perpendicular to the row orientation in either a northern or southern direction. Clipped samples were oven-dried and their corresponding tree number, transect direction, distance from tree, and dry weights were recorded.

Blimp and Cameras

The blimp was 5.5 m by 2 m with a capacity of 9 m^3 of helium. It produced a net lift of 4.7 kg when full. A braided nylon tether line was attached to keep it below a legal maximum altitude of 152 m. A home-made gondola held two Nikon® 6006 35 mm cameras aligned to photograph the same scene. Each camera was fitted with Nikon 28

mm wide-angle lens. The gondola contained two radio-controlled servos. One servo pressed a dual shutter release so that both cameras fire simultaneously. The second servo controlled a stepping motor that rotates the gondola to align shots.

Blimp Aerial Photos

On three separate occasions over a two-year period, aerial photos were obtained of the agroforestry replications. Photo sessions were timed to occur one or two days before the agroforests were grazed by sheep. These photos captured peak biomass production of the understory (forage) component. The agroforestry replicates were grazed two times during the growing season with the exact timing dependent on environmental conditions and forage growth. The photos used in this analysis were taken on June 26, 1994, just before the second grazing period. Photos were taken from an altitude of approximately 120 meters under a diffuse, but bright sky.

The cameras were loaded with Kodak ASA 100 Ektar® color print film and Kodak HIE® high-speed black and white infrared film. The color film was exposed through a haze filter with aperture and shutter speed automatically adjusted by the camera. The infrared film was exposed through a Wratten No. 25 (Red) filter that transmitted visible red as well as infrared spectral energy ranging from 0.59 μm to 0.90 μm. This "modified" infrared band was captured using a lens aperture manually set at f/16 with a shutter speed of 1/125 second.

Digital Elevation Model

A Digital Elevation Model (DEM) was produced using contours contained in two DXF files obtained from the City of Corvallis, Department of Planning. These files contain contours delineating every two feet of elevation. The hydrologic drainage,

streets, fences, and buildings were also delineated. The DEM has a resolution, or pixel size, of approximately 0.17 m on a side, or about 0.03 m^2, and maps an area 278 m by 224 m. The overall elevation change on our site is 21 m. Our agroforestry GIS database uses the Universal Transverse Mercator (UTM) Zone 10N coordinate system and the North American Datum (NAD) 1927.

Fence Line and Tree Positions

A Trimble Pathfinder Pro XL[*] Geo-Positioning System (GPS) was used to locate tree and fence positions for referencing to the DEM. The GPS was used to log at least 180 positions, in UTM coordinates, for each point location. These positions were differentially corrected using base station data from the Oregon State University, Department of Geosciences Base Station, and an averaged, corrected position was assigned to each point. The base station is located within a three kilometer radius from our site and provides accurate correction of geo-positioned points to within two meters (Trimble Navigation, 1991). Twelve trees in each agroforestry replication were geo-positioned. Corner fence posts and gates were geo-positioned on three separate dates. The final fence line positions were averages of the three corrected positions. In all instances, repeated positioning located points within a one meter radius of each other. Ground measurements were made between the fence line points and key trees to accurately locate the tree grid. One hundred and six GPS points and twenty ground measurements were used to locate and accurately align image layers (Cook and Pinder, 1996).

All corrected points were brought into AutoCad[*] as DXF files for the final fitting of an ideal tree grid. A perfect grid locating rows of trees seven meters apart with trees planted every two and a half meters was fitted visually to the GPS positions and fence line measurements. This best-fit grid was then used to supply coordinates for

Figure 3.2. Gray scale images of red, blue, green, and infrared bands.


Red

Blue

Green

Near Infrared
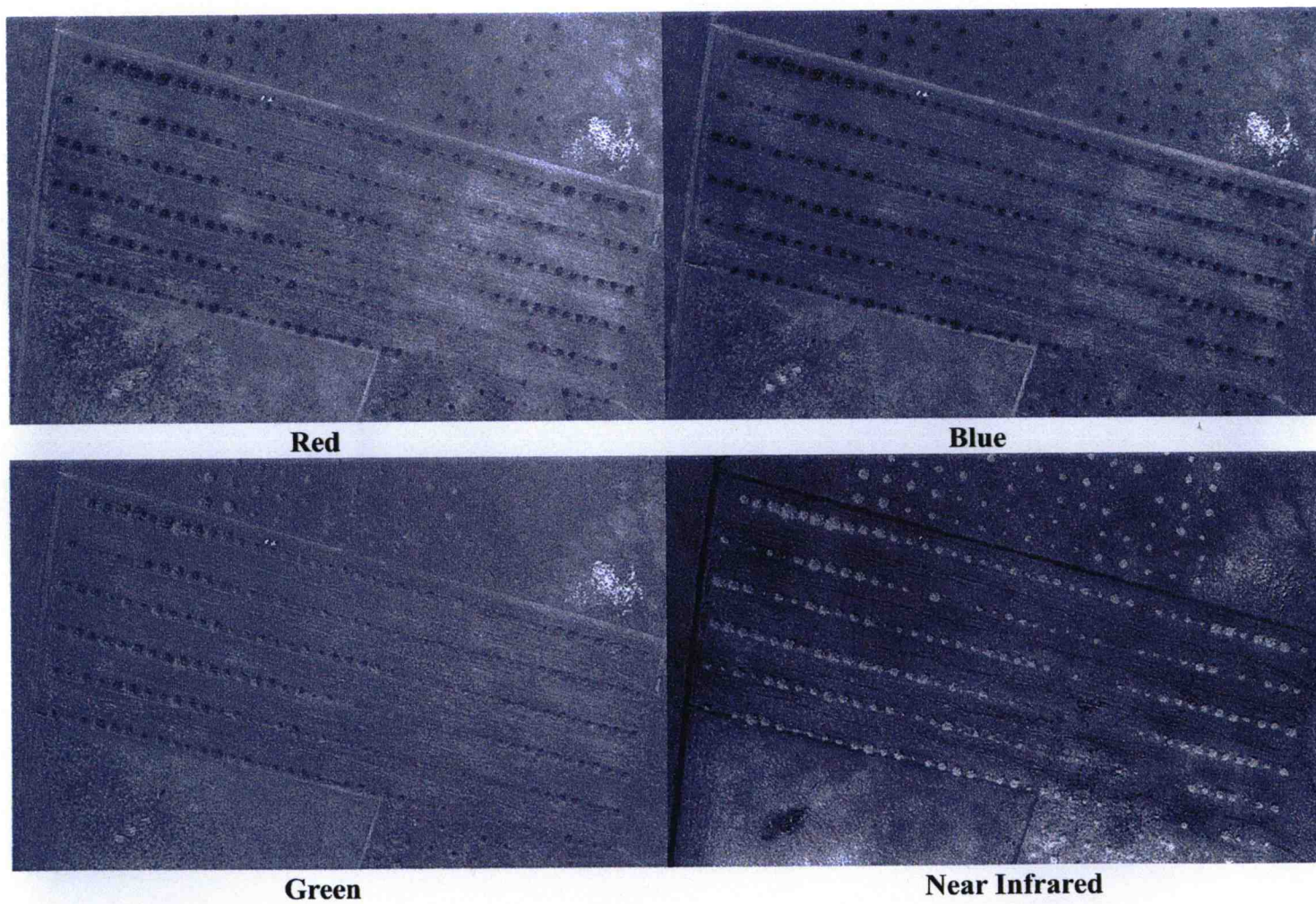
every tree in the agroforestry replications. These coordinates allow any identifiable tree to act as a Ground Control Point (GCP) during processing of aerial photos.

Photo and Image Processing

Photographic film was developed on the OSU campus at the Media and Communications Photo Center. Slides and negatives of the best paired-photos were then sent to LazerQwik® of Beaverton, Oregon, for processing using Kodak PhotoCD® technology (Kodak, 1994). The resulting PhotoCD contained 100 images available at five different resolutions. All analysis was done using images opened at full detail, or 3,072 columns by 2,048 rows. Color images were opened from the PhotoCD using Picture Publisher® software and were saved as 24-bit (true-color) Tagged Image File Format (TIFF) files. These color TIFF files were imported into the image processing software, Idrisi, and were converted into three digital color band images, red, green, and blue. Matching black and white infrared images were opened from the PhotoCD and were saved as 256-color paletted TIFF files. The TIFF files were then imported as a single, 256-color (grayband) image (see Figure 3.2).

Eighteen GCPs were used to resample each infrared band to the same relative coordinate grid as the matching color band images. A linear, nearest-neighbor resampling routine was used. The Root Mean Square (RMS) error for this operation was kept at less than 0.8 pixels for each image (Welch et al., 1995). Smaller-windowed images were extracted from each set of four waveband images to focus on agroforestry areas, to remove distorted photo edges, and to speed image processing times. A false color composite (FCC) was produced using the windowed green data for the blue band, the red data for the green band, and the infrared data for the red band (see Figure 3.3). The linear band saturation for this operation was set at 1.5 percent (Eastman, 1995). Points positioning tree trunks for clipping transects were interpolated on the FCC with on screen-digitizing. These points were resampled to a UTM Zone 10N coordinate

Figure 3.3. False Color Composite Image of Agroforestry "A" Plot.
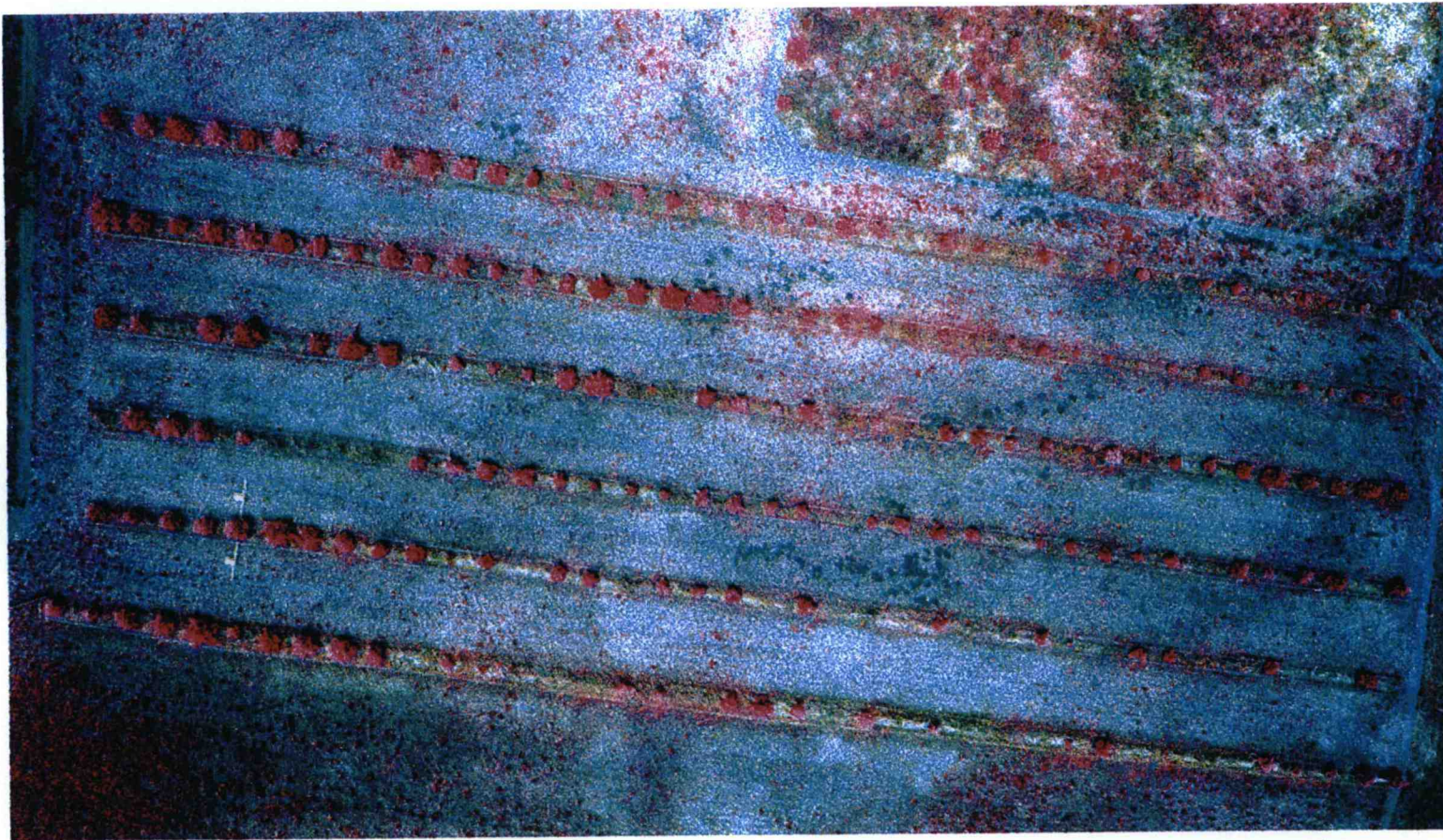
False Color Composite of Agroforestry A shows photosynthetically active biomass in shades of red.
Imagery was obtained on June 26, 1994

system and were converted into a DXF file for transfer into AutoCad. Clipped plot transects were digitized as polyline rectangles precisely 25 cm by 40 cm and were spaced 0.5 meters apart in the transect. A total of two hundred forty-four clipped plot polygons were designated for this set of pictures. The vector polygons were converted to raster format and were linked to the GIS database as extraction polygons. Average values of slope, aspect value, and elevation were extracted from GIS layers for each clipped plot polygon. The aspect value image is an aspect image that has been rescaled to show the degree of inclination north to south on a scale of 0 to 255 respectively. The extraction polygons were then resampled to the same relative coordinate system as the color bands to process the vegetative indices.

Training sites were identified, using the FCC image, for the five broad classes: bare ground, sparse cover, dense cover, tree, and shadow. Spectral signatures were extracted and identified (see Figure 3.4). A supervised classification using a maximum likelihood algorithm and equal probabilities was then used to produce a class cover layer (see Figure 3.5). These classification images were then reclassified to produce five Boolean, 0 or 1, layers isolating the separate classes. For example, the bare ground layer has ones to denote cells of bare ground with all other cells valued at 0. The extraction polygons were used to sum each component cover. Because cover pixels had a value of one, the sum total would identify how many pixels in each polygon were covered by each class. This sum was divided by the total number of pixels in the polygon, an average of 42, to generate percent cover estimates for soil, sparse vegetation, dense vegetation, shadows, and trees for each polygon. Thirty clipped plot polygons were located under tree canopies and were discarded from this analysis.

The modified infrared image contains visible red data values (see Figure 3.6) combined with infrared values. The decision to capture data over this range was made to fulfill other research objectives. However, the utility of infrared data is based on its high reflectance from vegetative biomass and low reflectance from bare soil, creating a wide range of values. The soil, in this instance, reflects strongly in the visible red range,

Figure 3.4. Spectral Signatures of Agroforestry "A" Classes.

Spectral Signatures for Agroforestry A
June 26, 1994
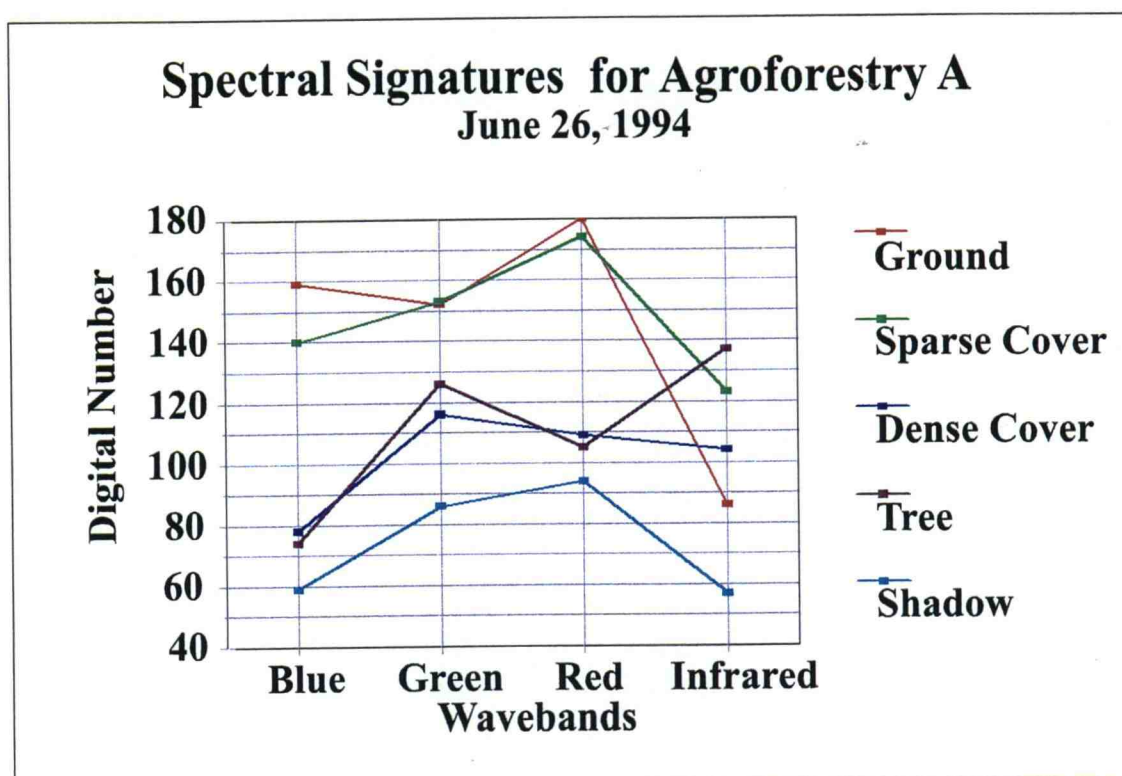
so the high red reflectance, even when combined with a low infrared reflectance, narrows the differences between bare soil and vegetation in the modified infrared band which makes the detection of vegetation more difficult. For this reason, the modified infrared images were digitally corrected to remove the red data values. Digital image processing allows one to construct mathematical functions using two image sets. We had an image containing the visible red data that we could subtract from the image containing red and infrared to produce an image containing only infrared (see Figure 3.7).

Digital number images were converted to reflectance values for the creation of vegetative indices. We wanted to know how the ratio between the visible color bands and the infrared band would be affected by varying the reflectance of the visible light band. Red and blue band images were scaled to produce three images for each color band representing 5, 10, and 15 percent reflectance of incident radiation. The infrared and red bands were then processed to form NDVIs using the formula:

$$NDVI = (Infrared - Red)/(Infrared + Red)$$

Three NDVI images were formed for each agroforestry replication with NDVI-5 using a red band of 5 percent, NDVI-10 using a red band of 10 percent, and NDVI-15 using a red band of 15 percent reflectance. The blue reflectance bands were combined with the infrared band in the same manner with the formula:

$$(B)NDVI = (Infrared - Blue)/(Infrared + Blue)$$

Three (B)NDVI were formed for each agroforestry replication with (B)NDVI-5 using blue at 5, (B)NDVI-10 using blue at 10, and (B)NDVI-15 using blue at 15 percent reflectance. Sums and averages of the vegetative indices within clipped plot polygons were extracted from the images for stepwise regression analysis (see Figure 3.8).

Figure 3.5. Supervised Classification of Agroforestry "A" Using Five Classes.
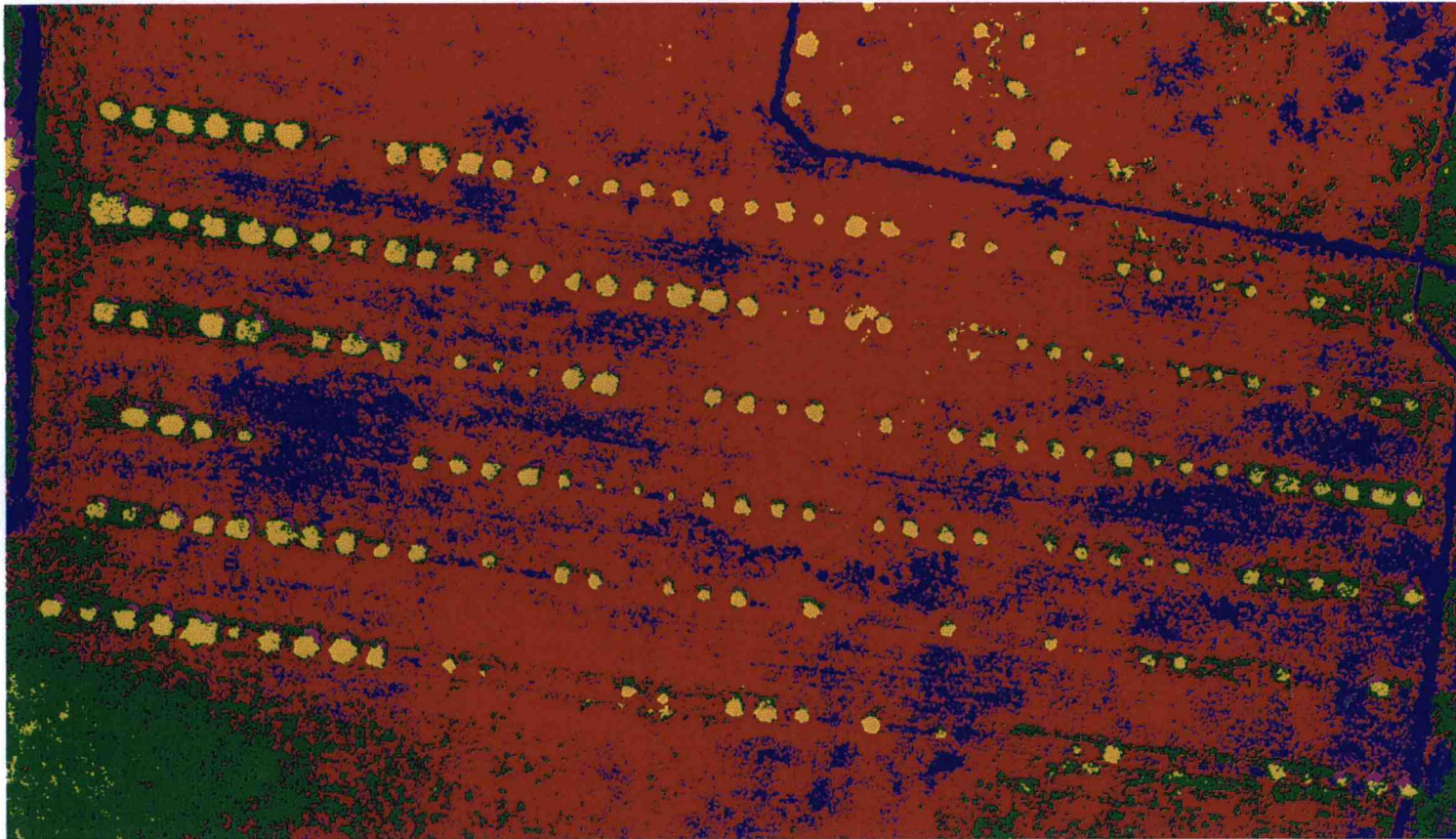
Supervised Classification Image showing five classes: trees (yellow), dense vegetation (green), sparse vegetation (red), bare ground (blue), and shadow (purple).

Results and Discussion

A visual examination of the databands (Figure 3.2) showed the infrared band to have the most distinct dataset, ie. it appears more detailed than the other bands. The second most detailed image of the set is not the red band, but the blue band. Trees appear darker and more distinct in the blue band, as are certain forage background patterns. Examination of band histograms reveals that both populations of data are normal in distribution with the blue band spanning a range of 136 values, while the red band spans 84. The blue band, in this case, appears to include more useful data than the red band. The spectral signatures for agroforest A (see Figure 3.4) show considerable variation in spectral response over the bands recorded. However, the classes bare ground and sparse vegetation share similar signatures in the visible light range. When the differences between values for the red and for the blue bands are examined, a greater difference between classes exists for the blue band than for the red. This difference also suggests that the blue band might be more suitable than the red band for quantifying vegetation.

A verification database was assembled from our GIS database consisting of twenty random, clipped plot polygons from each agroforest replication for a total of sixty samples. This database was used to evaluate and assess models generated by stepwise regression of the remainder of the clipped plot polygons data set (154 samples). Three other model database sets, one for each agroforest replicate, were assembled from the 154 samples. These were used to model understory dry weight response on an individual agroforest level. Each individual database contained at least 50 sample plots.

Regression analysis of data was conducted using linear, multiplicative, exponential, and reciprocal models. Linear models were selected because they most accurately estimated the verification dataset. Modeling on an individual agroforestry level, the best predictor for pasture dry weight biomass in Agroforest A was a model

Figure 3.6. Modified Infrared Band of Agroforestry "B".
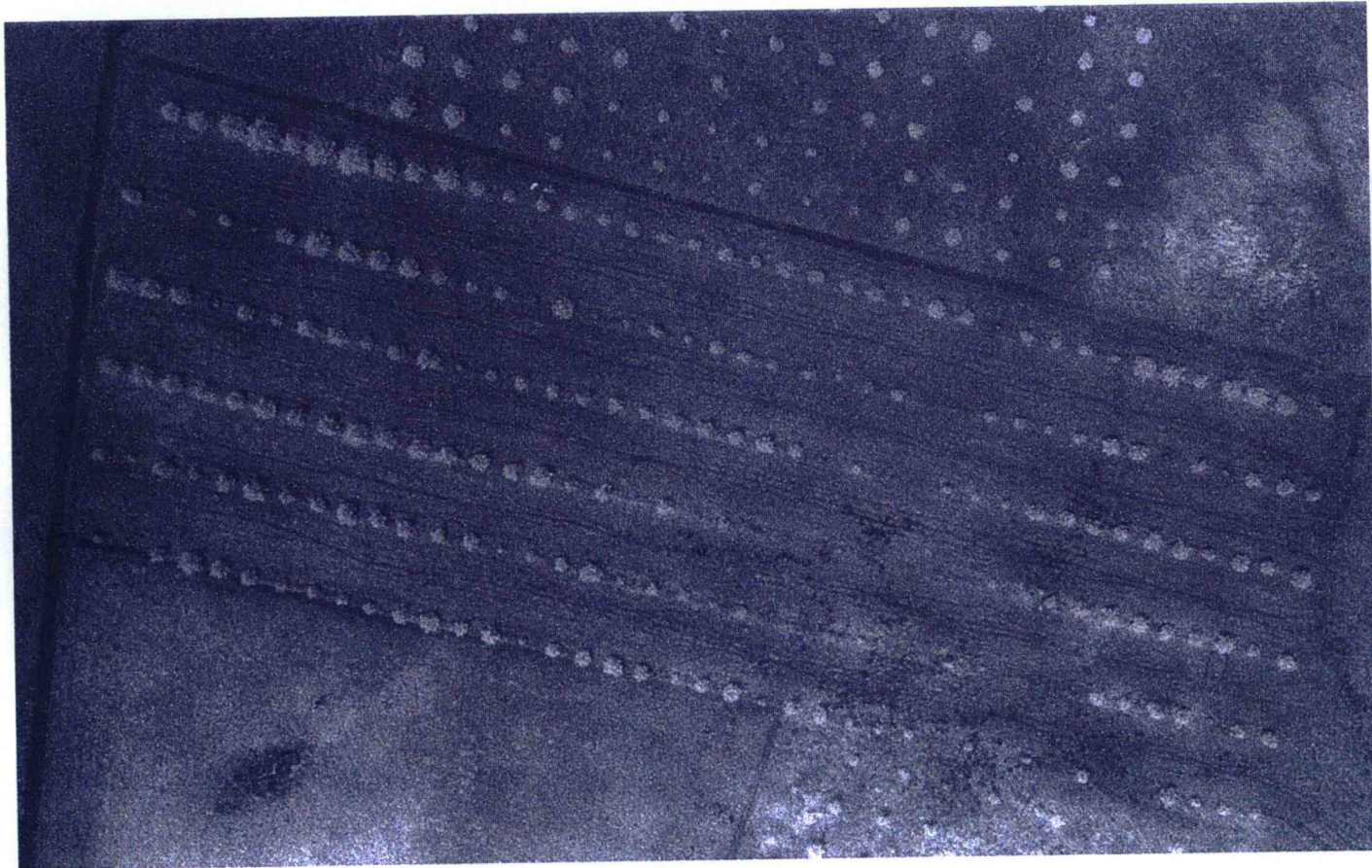
Modified infrared band contains red and infrared data values.

with an R^2 of 0.72 based on (B)NDVI-5. Agroforest B did not generate any useable regression models for the dry weight variable. The best model had an R^2 of 0.29. The best fit model for Agroforest C (R^2 of 0.65) was based on NDVI-15.

When all the agroforest replications were pooled, no suitable models were generated, the best R^2 being 0.36. Problems in pooling data across agroforests likely reflect substantial variation in both plant production and composition differences (see Figure 3.1). Of particular importance to remote sensing data, the percent cover of broadleaf plants (dicots) and grasses (monocots) was markedly different between agroforests.

	Broadleaf (%)	Grass (%)
Agroforest A	28.1*	64.8
Agroforest B	54.1*	40.6
Agroforest C	16.1*	83.3

* 7.1, 5.3, 0.5 % was subtracted from percentages to compensate for the summer death of subterranean clover (*Trifolium subterraneum L.*) so that data would better represent species composition at time of photos.

Accepting that considerable spectral differences exist in the broad groups, monocots and dicots, we created two general models, one for each broad species group. Because we adjusted our species composition data to reflect the summer death of subterranean clover, the total of broadleaf composition and grass composition does not equal one hundred percent for any agroforest replicate. Therefore, percentage composition using broadleaf plants defines a different model than percent composition grass does. We created two new variables, grasscomp and broadcomp, with the above

Figure 3.7. Pseudo-infrared Image of Agroforestry "B".
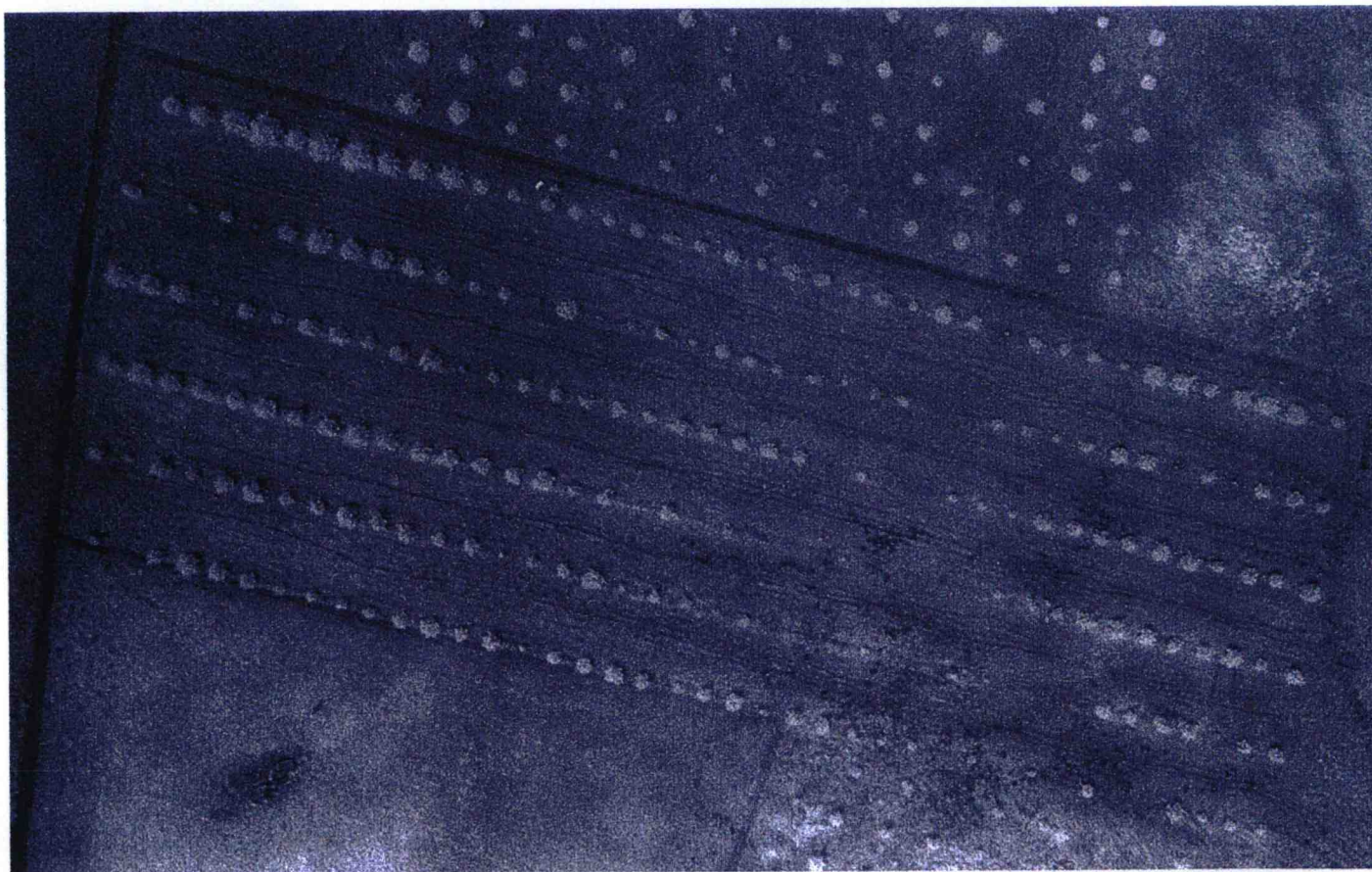
Red values have been digitally removed creating an infrared image.
(Note darkened areas showing bare ground with high red reflectance.)

values to incorporate percentage composition of grass and percentage composition of broadleaf plants into our analysis. When the variable broadcomp was added to the stepwise regression of all agroforests, a model with an adjusted R^2 of 0.9764 resulted. When the variable of grasscomp replaced it in the regression, a model with an adjusted R^2 of 0.9800 was produced. An examination of observed values plotted against estimates for each model shows three distinct clusters of points arranged along a strong regression line. The species composition data ranked, or stratified, the vegetative index values along the strong regression line between the agroforest replicates. In all, we generated two general models based on dominate species composition and two individual agroforest models (no model was generated for Agroforest B). These we labeled as Broadleaf (broadleaf plants dominate species composition), Grass (grass dominates species composition), Model A, and Model C.

The models were used to generate estimates of dry weight biomass for the sixty verification plots. Mean values and standard deviations of the estimates were compared to mean values and standard deviations of the actual dry weight to assess model accuracy for all three grouped replicates. Models were also compared on an individual agroforest level to select the best individual models (see Table 3.1).

Comparison of estimates to actual weights for the group of all three agroforestry replications showed the broadleaf and grass models producing estimates within 2 grams (200 kg/ha) of the actual mean value. This was an underestimate of approximately 10.5 percent. The standard deviation for the two models is about three times the deviation for the actual dry weight. The agroforest-specific models, A and C, did not preform well when applied to the entire data set. Model A produced an overestimate of 39 grams (3900 kg/ha) and Model C a nonsensical negative value. The broad agroforestry models, broadleaf and grass, tend to work well on their individual species-dominated replicates. The broadleaf model worked well with Agroforest B, 54.1 percent broadleaf, producing an over-estimate of less than 5 percent (108 kg/ha) and a standard deviation of 16.9, which is close to the actual weight standard deviation of 12.6 g/plot. This model has the

Table 3.1. Actual Dry Weights and Model Predictions.
All measurements are g/0.1m².

	Total All [1] Replications	Total [2] Agroforestry A	Total [2] Agroforestry B	Total [2] Agroforestry C
Actual Dry Weights	19.57	13.57	21.78	23.35
Standard Dev.	**9.43**	**5.53**	**12.64**	**5.28**
Broadleaf Model	17.60	15.13	22.87	31.51
Standard Dev.	**29.00**	**34.19**	**16.97**	**24.03**
Grass Model	17.42	14.79	16.36	21.11
Standard Dev.	**25.14**	**33.32**	**16.96**	**23.28**
Agroforest A Model	58.13	15.29	N/A	N/A
Standard Dev.	**43.01**	**16.31**	**N/A**	**N/A**
Agroforest C Model	-75.55	N/A	N/A	22.00
Standard Dev.	**80.49**	**N/A**	**N/A**	**17.06**

[1] Based on sixty sample plots, each 0.1m²
[2] Based on twenty sample plots, each 0.1m²

best fit of all models. However, the broadleaf model worked poorly on the grass dominated, Agroforest C, overestimating production by 37.2 percent (869 kg/ha). The Grass model, on the other hand, underestimated production by 9.6 percent (223 kg/ha). It also produced an estimate for grass-dominated Agroforest A, within 8.9 percent (121 kg/ha) of the actual mean. The models' standard deviations show considerable "wobble" in the range of values as they estimate dry weights.

The individual agroforest models were each successful in predicting biomass within their more limited situation. Model A produced an over-estimate of 12.7 percent (172 kg/ha), slightly larger than the Grass model. However, the standard deviation for this model is half of that for the species dominant models at 16.1 g/plot. Based on both mean value and standard deviation, Model A is the best fit model for Agroforest A. Model C underestimated production by 5.8 percent or 135 kg/ha. The standard deviation, at 17.1 g/plot, is about three times the actual standard deviation of clipped plots. Model C was clearly the best model for Agroforest C.

Broadleaf Model

Dry Weight = ((B)NDVI-10 - 70.668498+0.011453(Tree height) -
0.607454(Distance from tree) - 8.495667(Percent bare ground) -
0.009179(Aspect Value) - 0.267925(Elevation) - 0.56318(Percent
composition broadleaf))/0.060461

Grass Model

Dry Weight = ((B)NDVI-10 + 16.368162-0.887642(Distance from tree) -
5.526492(Percent bare ground) + 0.575005(Percent composition
grass))/0.057974

Model A

Dry Weight = ((B)NDVI-15 - 21.901926-0.224624(Trunk diameter) -

1.335103(Distance from tree) + 0.000001734592(Tree volume) -

.019249(Percent bare ground))/0.122034

Model C

Dry Weight = (NDVI-15 - 29.548379-1.567157(Distance from tree) -

4.286467(Sparse vegetation cover) + 0.017672(Aspect Value))/0.112156

The variable distance to tree has a universal effect in these agroforest replications as it appears in all models. If the coefficient were positive, it would indicate that the tree is a "bad neighbor" and that competition dominates interactions with the forage. However, our distance coefficient is negative. A negative regression coefficient might indicate that facilitative effects such as tree shading the ground or decreasing wind velocity are important. Animal behavior is also a possible explanation. When sheep graze the replications, electric fence is strung along either side of the tree rows to prevent browse damage. The sheep and native deer tend to walk down the middle of the rows staying as far from the fence wire as possible. This activity tends to create paths which might be reflected in forage biomass distribution (see Figure 3.8). It should be noted that our regression models depict standing forage biomass at a point in time, which is the net result of previous forage production, use, and tissue senescence.

Because the vegetative indices are not soil-linked, it is not surprising to see a soil-linked variable in the model with the appropriate negative coefficient. A plot with more bare ground produces less biomass. Model C uses sparse vegetation cover instead of bare ground. Perhaps with a grass monoculture, the upright architecture of the grass plants allows soil background pixels to be better incorporated in the sparse vegetation class than with the bare ground class. Tree variables relating to size (height and

Figure 3.8. Blue Difference Vegetation Index (BNDVI) of Agroforestry "B" Showing the Position of Clipped Quadrats.

This index generated the best performing model.
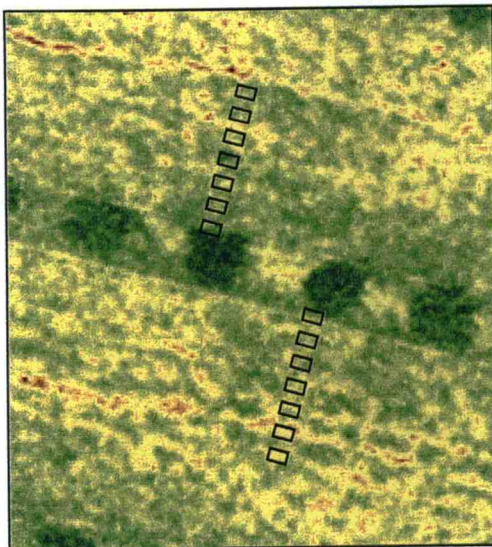
Sheep paths are shown running down the middle of rows. In the windowed image, paths are shown in more detail. The effects of paths might be reflected in the model variable, distance from trees. This variable occurs in all of the models with a negative coefficient.

volume) appear with positive coefficients. It is possible that this relates to site suitability. Better areas grow bigger trees and produce more forage biomass.

A final variable, aspect value, appeared in the models Broadleaf and Model C but with opposite signs on the coefficients. Does this mean broadleaf plants prefer wetter, cooler northern sites while grasses prefer warm, sunny south facing slopes? When we extract the average agroforestry value from the aspect image, we discover that Agroforest A and B are oriented to the northeast. However, Agroforest C is oriented to the northwest. Slope of the site is less than 8%, so physical aspect differences are probably not great. We cannot tell, at this time, if the different preferences for north or south demonstrated by the Broadleaf Model and Model C are based on species preferences, dicots versus monocots, or on overall agroforestry aspect.

Figure 3.9 shows a predictive model for agroforest C. The greenest forage represents 4000 kg/ha while the tan color represents 1000 kg/ha. The effect of distance from tree in driving the model is seen by the color bands radiating along the tree rows.

Conclusions

Our study demonstrates the value of the blue wavelength (0.40 μm to 0.50 μm) for modeling dry weight biomass. The value of this data was dependent upon accurate measuring techniques that required a low-level sensing platform. Varying the reflectance values of the visible band did not improve vegetation estimates as best fit models still used red and blue normal daylight reflectance values of 0.15 and 0.10 respectively. Our best fit regression models were able to predict forage biomass within 100-135 kg/ha, which was comparable to the accuracy generally achieved by physical techniques such as clipping plots. Species composition of forage was extremely important in accurately model vegetation response. General models based on dominant species, dicot or monocot, work well on plots dominated by those groups. Therefore,

Figure 3.9. Predicted Standing Crop for Agroforestry "C" Modeled at 135 Levels of Production.
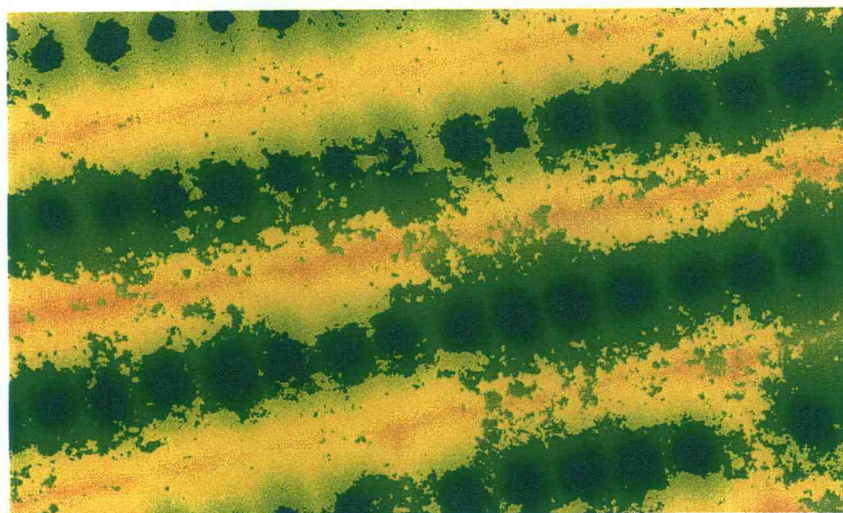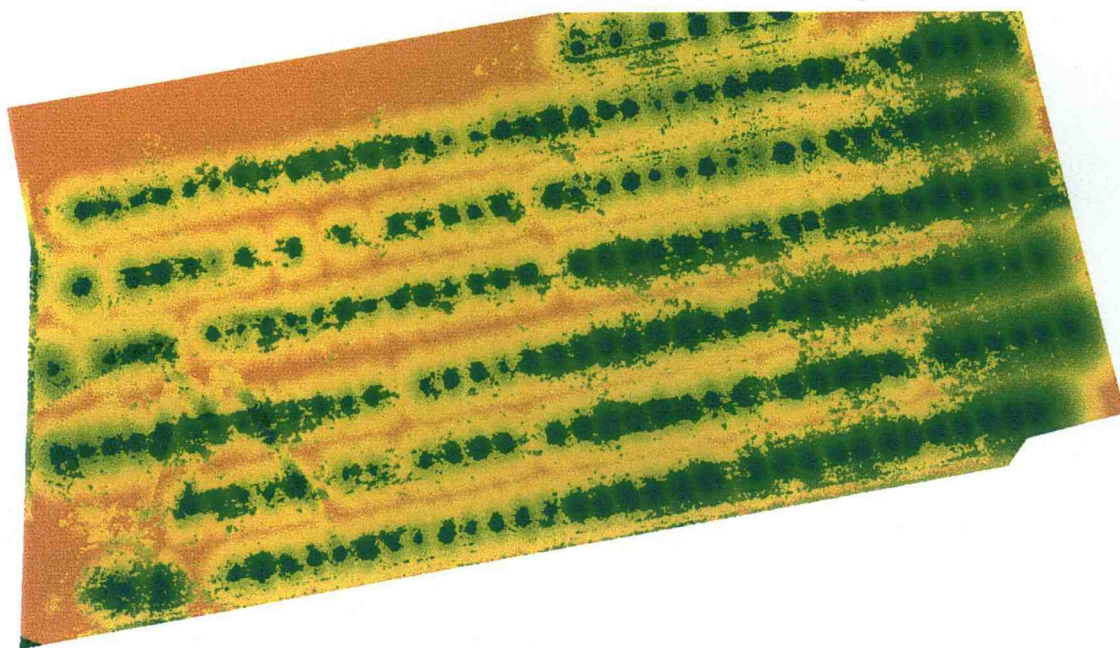
Window from above image shows dry weight biomass as modeled
at 135 levels of production.

separate models may not be needed for each image set. Finally, Geographic Information Systems coupled with remote sensing was a powerful tool for describing small scale landscapes and developing a better understanding of landscape processes. A GIS-linked database can incorporate spatial, physical, and spectral data, and can combine factors in a new way to explain the variability encountered in nature.

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Chapter 4

Summary

Our research produced results that fulfilled most of the objectives with which we started. Analysis and modeling of photosynthetically active radiation data verified our shadow modeling and showed that the aboveground factor, solar energy, was available in different amounts on opposite sides of the trees. In turn, pattern analysis strongly suggests that underground factors, soil moisture and available nutrients, exert the greatest influence on understory production in our agroforestry research plots. This result was further bolstered by the results from low-level remote sensing analysis, which did not produce different regression models for opposite sides of agroforestry trees but only produced models that worked on both sides of the tree equally well. Remote sensing, geographic information systems, and global positioning systems technologies proved to be powerful research tools for gathering and storing spatial data, combined information from different sources, manipulated and analyzed spatial data, and produced visual representations of results. Regression modeling of spatial data produced interesting, and potentially enlightening, models that mathematically describe ecological processes. These results were supported by a large body of research on plant competition and were consistent with our understanding of ecological processes.

The unexpected influence of animal use patterns, primarily trails, was shown using classical physical techniques, clipping of biomass, as well as by using pattern analysis and remote sensing techniques. This influence is relatively unknown and suggests an area for continued research to develop a better understanding of its magnitude. Such research would greatly benefit silvopastoral design and management.

In summary, our work meets the requirements of accepted research. It presents strong evidence in support of our objectives. The evidence is supported by our understanding of physiological and ecological processes. More importantly, it brings

more questions to mind than answers it produces. This is the role of research in our society.

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APPENDICES

Appendix 1

The availability of solar energy on a site is dependent upon latitude, season, and weather patterns. The first two variables can be calculated and used to predict available solar energy for a site at a specific time given an effect from the weather. The relationship of these variables becomes obvious when one examines the trajectory of the earth around the sun. The earth travels an elliptical path around the sun, even though it is not a very pronounced ellipse. The earth is closest to the sun in December at 89.8 million miles and farthest from the sun in June at 95.9 million miles. Because the intercepted radiation decreases with the square of the distance, the relatively small difference in distance makes an appreciable difference in radiation intensity. Those of us living in the northern hemisphere should wonder, "Why isn't it warmer in January then if we are closer to the sun?" The seasonal effect, winter versus summer, is not related to distance from the sun but to the tilt of the earth's axis in relationship to the solar plane. The rotation about this axis combined with the orbit about the sun causes considerable seasonal variation in the apparent daily path the sun traces across the sky. On June 22, the summer solstice, a ray drawn from the sun forms a 23.45° angle above the earth's equator as viewed from the Northern Hemisphere. On the other hand, a ray drawn on the winter solstice, December 22, forms an angle of 23.45° below the equator. On the vernal and autumnal equinoxes, the sun is directly over the equator. This angle in relation to the equatorial plane is called the solar declination, δ, and can be calculated for any day of the year using the following relationship:

$$\delta = 23.45 \, sin \, [360 \times (284 + N)/365]$$

where N is the Julian day, N = 1 is January 1 and N = 365 is December 31.

Table A1.1. Solar Declination for the Fifteenth of Each Month and Solstices and Solar Noon Altitude and Day Length for Agroforestry Site at Corvallis, Oregon (44°33' N, 123°20' W).

Month	Julian Day	Solar Declination δ (degrees)	Solar Noon Altitude α_N (degrees)	Day Length to nearest 0.5 hour (hours)
January	15	-21.27	24.11	8.5
February	46	-13.29	32.09	10.0
March	74	-2.82	42.56	11.5
April	105	9.41	54.79	13.5
May	135	18.79	64.17	14.5
June	166	23.31	68.69	15.0
June 21*	172	23.45	68.83	15.5
July	196	21.52	66.90	15.0
August	227	13.78	59.16	14.0
September	258	2.22	47.60	12.0
October	288	-9.60	35.78	10.5
November	319	-19.15	26.23	9.0
December	349	-23.34	22.04	8.5
December 21*	355	-23.45	21.93	8.0

* Summer and winter solstices

The apparent daily solar path is described using two component angles, an altitude angle, α, and an azimuth angle, a_s. The altitude angle at solar noon, α_N, is obtained from the formula:

$$\alpha_N = 90° - L + \delta$$

where L =Latitude, 44°33' or 44.62° for our site. We can then calculate the highest point and the lowest noon angle the sun will ever obtain for our sky (Table A1.1). Therefore, at solar noon on June 22, the summer solstice, the sun will be at an altitude of 68.83° above a level horizon with an azimuth of 180°, true south. By definition, the solar azimuth angle of 180° is solar noon. On the winter solstice, December 22, solar noon will produce an altitude angle of 21.93°. The closer the altitude angle nudges toward perpendicular, or 90°, higher levels of solar anergy fall per unit area of ground. This energy is expressed as the greater amounts of solar heat and higher light levels of summer.

The sun's altitude angle can be calculated for any time of the day using the relationship:

$$sin\ \alpha = cos\ L\ cos\ \delta\ cos\ h \div sin\ L\ sin\ \delta$$

where h is called the hour angle and is equal to 15° for each hour away from solar noon. The azimuth angle at any time is given by the relationship:

$$sin\ a_s = (cos\ \delta\ sin\ h) / cos\ \alpha$$

The results of these calculations for our site on the fifteen of each month are shown in Figure A1.1. In order to further tie our solar calculations to our PAR data, we have to convert solar time (ST) to match the local time (LT) recorded by the dataloggers. This

Figure A1.1. Solar Altitude and Azimuth for Agroforestry Plots at Corvallis, Oregon.
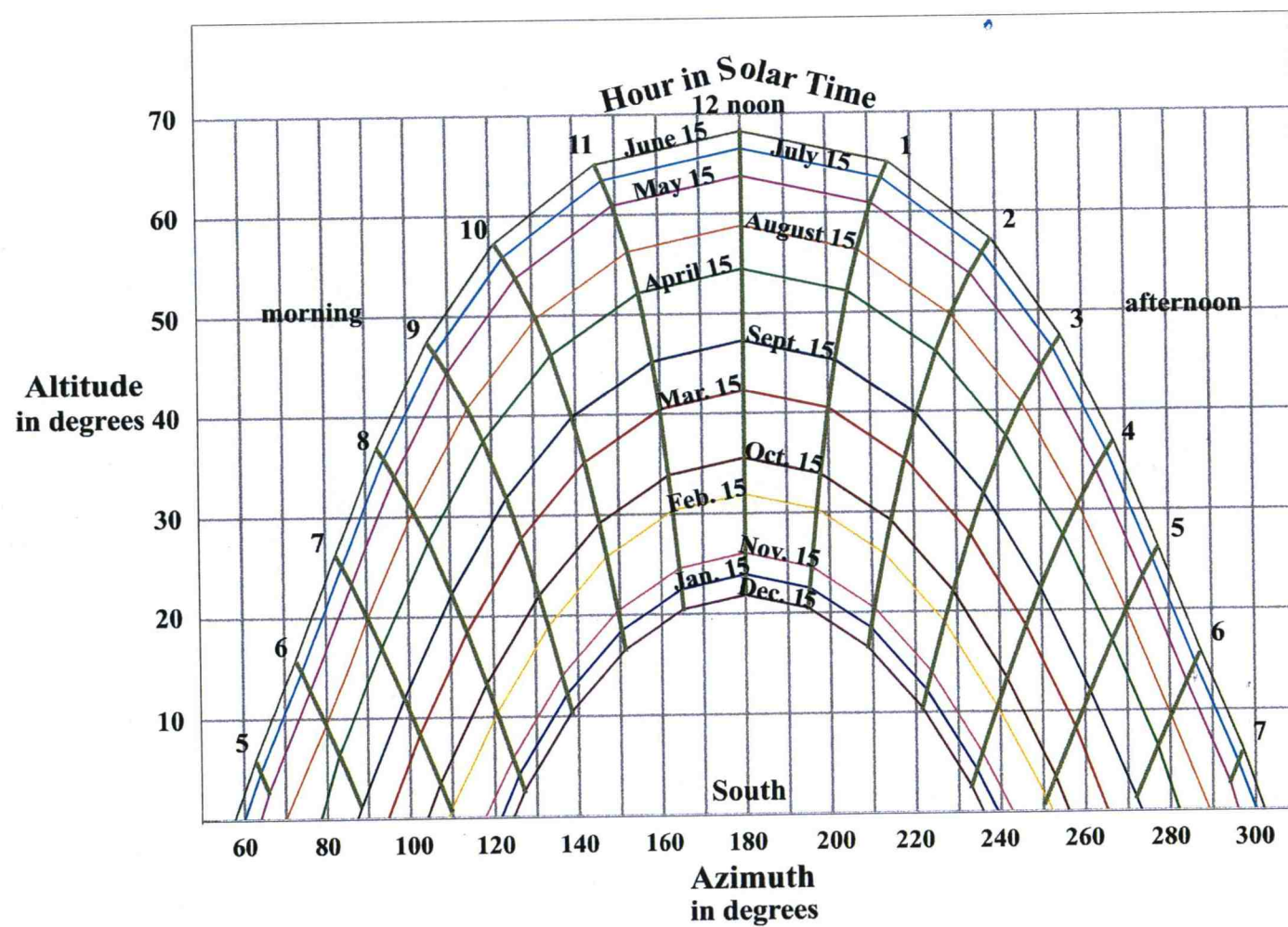
operation is accomplished by the following formula:

$$ST = LT + 4(LT_{meridian} - longitude) + E$$

where $LT_{meridian}$ is the local time meridian, given for the various United States time zones in Table A1.2; and where E is a factor called the equation of time, which corrects for various earth-orbit phenomena. E is interpolated from Figure A1.2. Summer's daylight savings time requires an hour to be added to the answer from the above formula.

A comparison of the PAR data with the graph of solar altitude and azimuth shows some differences for the approximate day length throughout the seasons. The PAR data for December shows a solar day of approximately eight and one-half hours with maximum values reaching 948 μmols s^{-1} m^{-2} and an average solar noon value of 325 μmols s^{-1} m^{-2}. The length of day for this month is the approximately the same as that obtained from our solar graph. On the other hand, the PAR data for early July shows a solar day spanning seventeen hours with maximum values reaching 2010 μmols s^{-1} m^{-2}. The average value for solar noon is about 1820 μmols s^{-1} m^{-2}. However, the solar graph indicates a day length of only fifteen hours. The effect of a higher solar path provides enough diffuse skylight for between one to two hours of additional PAR recordings at this time. For this month, the readings for the first and last hours of the day ranged from near the minimum PAR threshold of 10 μmols s^{-1} m^{-2} to around 200 μmols s^{-1} m^{-2}. The benefit of this twilight activity would vary among the plant population. Species with low light compensatory levels and an upright canopy structure would continue growth processes for a longer period each day. The fact that the maximum PAR value for December is half of the July maximum, while the average is less than one-fifth, is representative of the rainy, cloud-filled skies of winter. For convenience, the terms north and south have been used to describe directional clipping and PAR data. However, an examination of the GIS database (Figure A1.3) shows that the agroforestry tree grids are actually oriented at an azimuth value of 60°on a grid where true north is 0°and due east is 90°. Because the PAR sensor arrays were

Table A1.2. The Local Time Meridians for United States Standard Time Zones

Time Zone	LT-meridian
Eastern	75°
Central	90°
Mountain	105°
Pacific	120°
Yukon	135°
Alaska-Hawaii	150°

positioned to correspond to clipping transects, namely perpendicular to tree rows, they are not oriented to the true north-south axis of the solar path across the sky. The north transect actually has a azimuth value of 330° while the south transect has a value of 150°. Using the above formulas, we can calculate the solar altitude for a solar azimuth of 150° or the point when the tree is directly in line between the sun and the north PAR sensor array. In this position, the tree is casting its shadow directly down the sensor array. Using the solar altitude angle and the tree's height, we can then calculate the length of the shadow cast on level ground (Table A1.3). For the sake of comparison, the shadow lengths for a representative tree measuring 250 cm in height were also calculated to show shadows as they vary with the season.

The calculated shadow lengths for a tree 250 cm in height demonstrate that, on level ground, tree shadows will affect all northern clipping positions from the beginning of October until the beginning of March. During this time, southern clipping positions will start to experience shading with tree shadows stretching across the entire alley for long periods in December and January. However, cold temperatures would be the main limit on any photosynthesis during this time. A comparison of PAR readings from the south transect, using the sensors located 1.0, 1.5, and 2.0 m from the tree, and the open pasture sensor showed no significant differences between the two locations for the time periods measured. In other words, locations directly south of representative trees receive the same amount of photosynthetically active radiation as open sites. Direct comparisons between north and south transect plots were also made when simultaneous recordings were made on both sides. These comparisons showed that north transect positions at lag distances 3.0 and 3.5 m were not significantly different from south transect positions at lag distances 1.0, 1.5, and 2.0 m. The major effects of shading were localized to within 2.5 m north of a tree. One further reference to the solar graph should be made at this time. An examination of azimuth angles reveals that from the end of March until the end of September, the sun actually rises and sets to the north of the east-west axis of 90° to 270°. The amount of sunshine from this northern position reaches a maximum of about six hours during the summer solstice providing light for
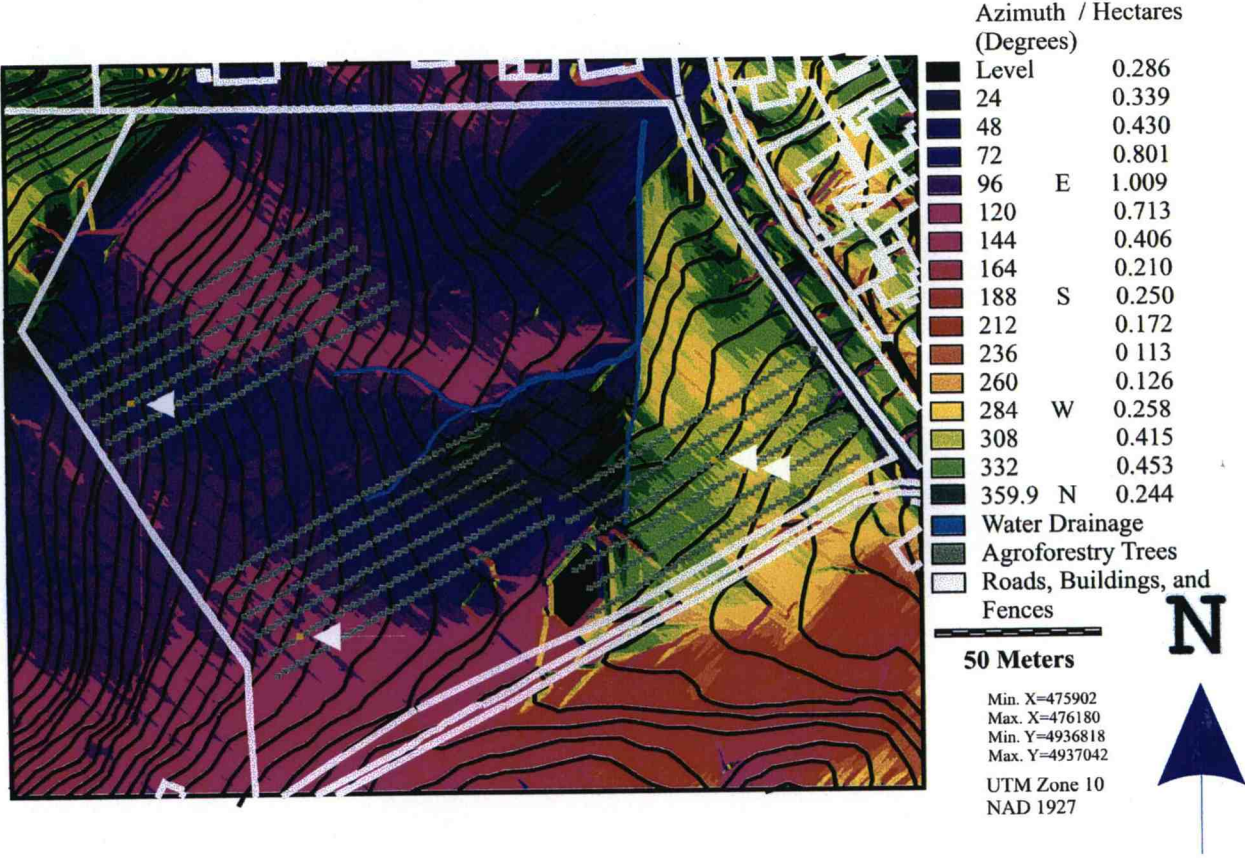
Figure A1.2. Equation of Time
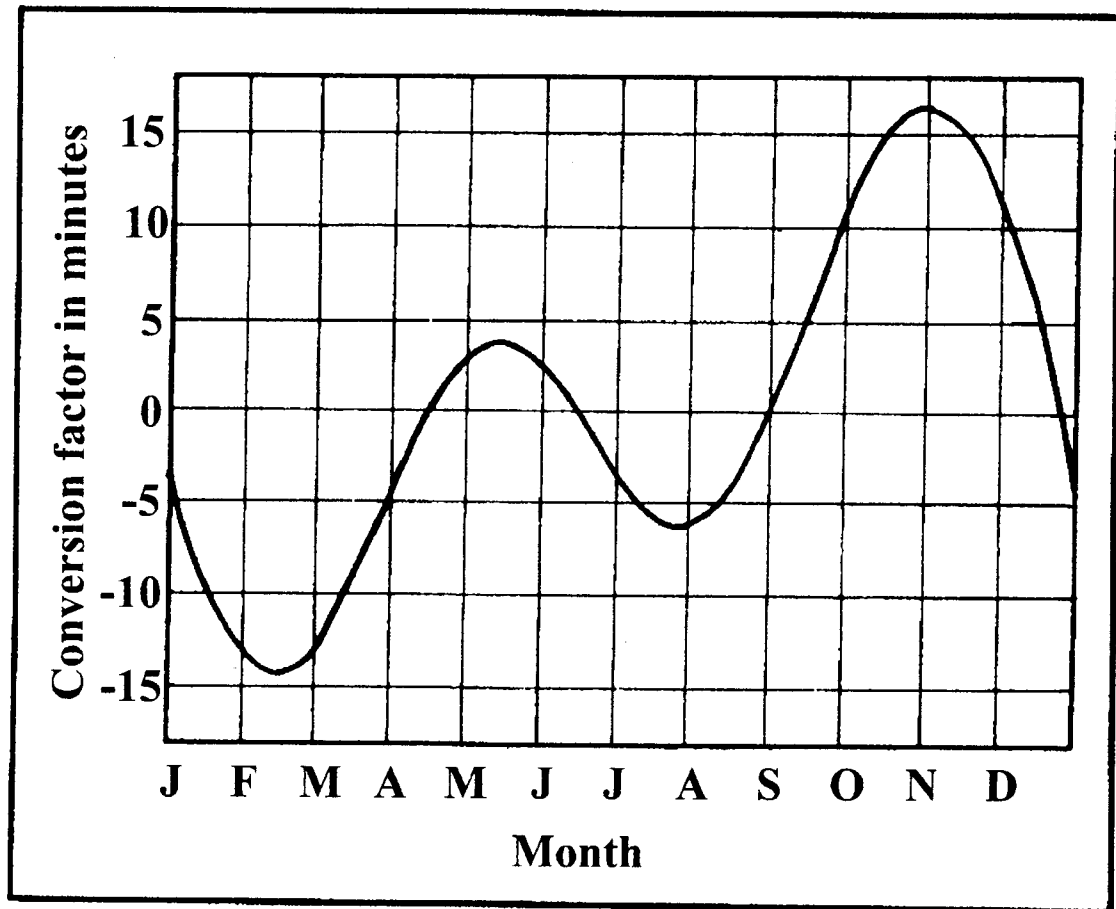
From Leckie, J., G. Masters, H. Whitehorse, and L. Young. 1981. Solar Thermal Applications. IN: More Other Homes and Garbage, Designs for Self-sufficient Living. Sierra Club Books, San Francisco, CA, pp 95-240.

plant growth to the north of shading obstacles. This solar position north of the east-west axis combined with the 60° aspect angle of the tree grid allows shadows from neighboring trees to sometimes affect the PAR values for southern transects (Figure A1.4). The 60°tree grid matches the northeasternmost solar aspect angle, so the morning sun seldom shines on the northern side of the tree rows. However, the afternoon sun shines on the northern side of tree rows for most of the year, from January 20 to November 20, with neighboring tree shadows affecting some southern transect positions. In June and July, the sun is north of the tree grid for over five hours in the afternoon. Neighboring tree shadows predominately affect positions 2.5 and 3.5 meters south of the observation tree with PAR readings dropping to as low as 24 percent of available daylight. This pattern of late afternoon shading of southern PAR transects is apparent in graphs for April, May, June, July, August, and September. The degree of shading and the affected positions in the transect are determined by neighboring tree height, the solar descent altitude and azimuth angles, slope, and aspect of the slope. Overall shading reduced first period readings at south lag distances 2.0, 2.5, and 3.5 m, to 97, 93, and 91 percent of the maximum PAR readings (Table A1.4). For a comparison north lag distances 1.0, 1.5, 2.0 and 2.5 m were reduced to 49, 78, 92, and 96 percent of the maximum readings. For the second period, only the position 3.5 m south of a tree was affected with 96 percent of the maximum value. North transect positions at 1.0 and 1.5 m produced readings of 56 and 91 percent of maximum. The data indicates that with a tree grid of this spacing , we also experience some slight shading to the south of the tree.

(Formulas were taken from American Society of Heating, Refrigerating, and Air Conditioning Engineers Handbook of Fundamentals. 1991. ASHRAE New York, NY 638p.)

Figure A1.3. Aspect of the Slopes of Witham Hill with OSU Rangeland Resources Agroforestry Research Plots in Corvallis, Oregon.

Azimuth / Hectares (Degrees)		
Level		0.286
24		0.339
48		0.430
72		0.801
96	E	1.009
120		0.713
144		0.406
164		0.210
188	S	0.250
212		0.172
236		0 113
260		0.126
284	W	0.258
308		0.415
332		0.453
359.9	N	0.244

Water Drainage
Agroforestry Trees
Roads, Buildings, and
Fences

50 Meters

Min. X=475902
Max. X=476180
Min. Y=4936818
Max. Y=4937042

UTM Zone 10
NAD 1927

N

The map represents an area of 278 meters by 224 meters, or 6.2 hectares. The aspect, or orientation, of the slope affects soil moisture levels, heat loads, as well as light intensity levels. Arrows show trees used for PAR measurements. Contours spaced every two feet, in black, give an indication of the slope.

Table A1.3. North PAR Data Collection Periods with Local Time for Solar Noon, Solar and Local Time for Solar Azimuth 150° (tree shadow aligned with PAR sensors), Solar Altitude, Calculated Shadow Length of Actual Tree, and Calculated Shadow Length of 250 cm Tree.

All values are the means for the collection periods.

Time is given using a 24 hour clock.

Time Period	Solar Noon Local Time*	Solar Time at Azimuth 150°	Local Time* at Azimuth 150°	Solar Altitude at Azimuth 150° (degrees)	Shadow Length Actual Tree (cm)	Shadow Length 250 cm Tree (cm)
Feb. 22 -Mar. 5	12:16	10:18	10:34	31.79	455	403
Apr. 26 -May 5	13:06	10:55	12:01	57.05	183	162
May 17 -22	13:06	11:03	12:16	62.52	147	130
June 14 -27	13:10	11:10	12:19	66.41	117	109
July 10 -18	13:11	11:07	12:18	64.52	119	119
August 9 -17	13:11	10:54	12:05	56.70	164	164
Sept. 24 -Oct 4	13:02	10:27	11:28	37.59	540	325
Dec 6-16	12:05	09:54	09:59	16.43	844	848

*Local time is adjusted to show daylight savings time where applicable.

Figure A1.4. Average PAR Readings for Average Day and Observed Trees' Height.
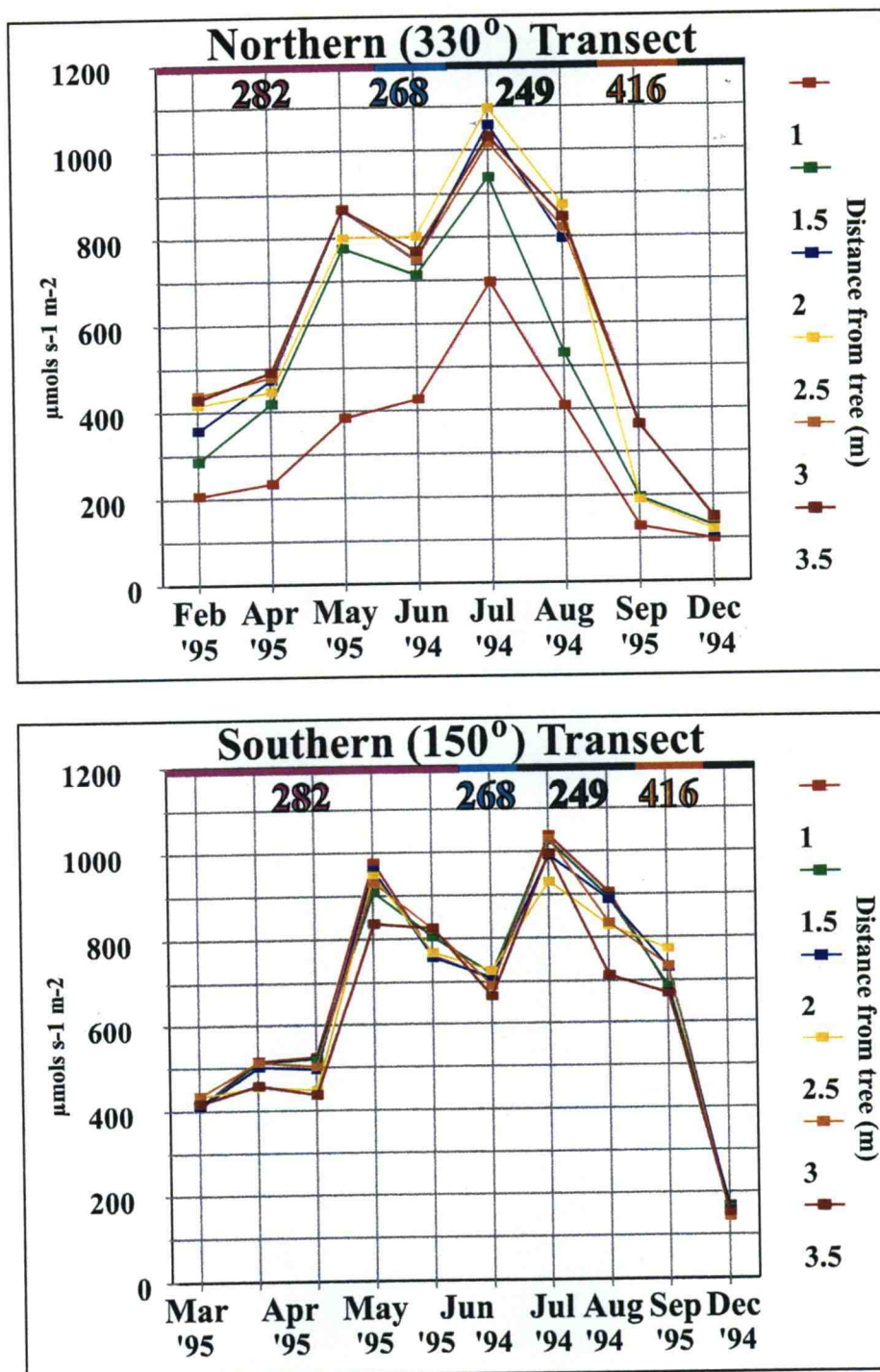
Tree heights are shown as colored numbers and are given in cm.
Observation periods were not consecutive. Year of observation shown.

Appendix 2

Table A2.1. Clipping Biomass for Root Barrier Plots for May 17-20, 1994

Tree Number	Direction N or S	Height in cm	Diameter in mm	Canopy Diameter in cm	1.0 m from Tree gm	1.5 m from Tree gm	2.0 m from Tree gm	2.5 m from Tree gm	3.0 m from Tree gm
106	N	236	46	132	20.2	21.1	18.3	24.1	15.7
198	S	280	52	143	26.8	27.3	28.3	27.4	21.4
465	N	234	61	157	24.8	30.6	33.9	27.1	16.4
527	S	252	56	177	21.2	34.6	21.7	17.4	14.6
789	N	207	42	129	20.9	29.1	32.4	27.7	22.4
796	S	206	53	150	13.1	23.6	23.5	21.5	20.2

Table A2.2. Clipping Biomass for Root Barrier Plots for June 26 - July 7, 1994

Tree Number	Direction N or S	Height in cm	Diameter in mm	Canopy Diameter in cm	1.0 m from Tree gm	1.5 m from Tree gm	2.0 m from Tree gm	2.5 m from Tree gm	3.0 m from Tree gm
106	N	236	46	153	30.2	24.4	24.2	27.5	24.5
198	S	280	52	166	24.5	33.9	29.7	39.7	50.5
465	N	234	61	197	25.4	17.7	14.7	14.7	11.9
527	S	252	56	177	0.0	34.3	18.2	17.5	12.9
789	N	207	42	129	21.0	41.6	17.8	21.8	26.0
796	S	206	53	150	16.4	19.2	24.5	18.8	29.1

Table A2.3. Clipping Biomass for Root Barrier Plots for May 22, 1995.

Tree Number	Direction N or S	Height in cm	Diameter in mm	Canopy Diameter in cm	1.0 m from Tree gm	1.5 m from Tree gm	2.0 m from Tree gm	2.5 m from Tree gm	3.0 m from Tree gm
106	N	290	75	187	43.2	47.3	45.0	44.1	36.1
198	S	307	67	203	48.4	42.1	43.5	56.0	54.6
465	N	318	80	221	39.4	39.0	63.0	50.2	32.1
527	S	326	80	256	39.5	63.2	61.9	68.4	45.1
789	N	died	died	died	29.7	36.9	31.4	36.0	48.4
796	S	241	76	164	41.2	51.2	42.8	46.3	50.3

Table A2.4. Clipping Biomass for Control Trees for Root Barrier Plots for May 17-20, 1994

Tree Number	Direction N or S	Height in cm	Diameter in mm	Canopy Diameter in cm	1.0 m from Tree gm	1.5 m from Tree gm	2.0 m from Tree gm	2.5 m from Tree gm	3.0 m from Tree gm
108	N	209	43	136	18.6	19.4	22.8	20.2	30.5
191	S	237	45	150	24.5	37.8	22.8	22.9	37.1
463	N	236	42	144	26.0	22.2	22.3	14.2	18.8
528	S	240	59	185	23.1	33.0	25.4	24.7	21.7
790	N	198	39	121	37.8	28.4	15.2	21.6	22.4
797	S	208	50	118	19.0	24.0	19.6	16.3	22.0

Table A2.5. Clipping Biomass for Control Trees for Root Barrier Plots for June 26 - July 7, 1994

Tree Number	Direction N or S	Height in cm	Diameter in mm	Canopy Diameter in cm	1.0 m from Tree gm	1.5 m from Tree gm	2.0 m from Tree gm	2.5 m from Tree gm	3.0 m from Tree gm
108	N	209	43	136	36.6	31.3	19.5	19.1	21.2
191	S	237	45	150	19.8	23.4	18.5	31.4	17.5
463	N	236	42	144	22.3	18.1	19.8	14.7	26.9
529	S	278	54	204	27.2	12.9	16.8	12.3	8.7
790	N	198	39	121	27.8	27.3	19.6	13.4	14.3
797	S	208	50	118	20.5	30.9	21.4	37.6	27.8

Table A2.6. Clipping Biomass for Control Trees for Root Barrier Plots for May 22, 1995.

Tree Number	Direction N or S	Height in cm	Diameter in mm	Canopy Diameter in cm	1.0 m from Tree gm	1.5 m from Tree gm	2.0 m from Tree gm	2.5 m from Tree gm	3.0 m from Tree gm
108	N	281	67	163	44.6	45.0	41.4	49.7	45.5
191	S	324	67	193	51.3	49.6	61.6	54.6	54.9
463	N	306*	67	187	32.9	48.2	49.7	40.5	41.8
529	S	390	90	245	47.3	49.4	57.9	59.4	57.6
790	N	234*	52	154	63.7	55.3	41.4	55.4	0.0[1]
797	S	276	66	143	53.1	67.6	61.7	52.4	52.7

*late measurement 7/95
[1] mole hill