SILVOPASTURE AS AN APPROACH TO ENHANCING PHOSPHORUS AND NITRATE RETENTION IN PASTURELANDS OF FLORIDA

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2006

To my beloved wife Daphnée B. Michel, my precious son Alain-Christian Michel, my adored mother Germaine D. Michel and to the loving memory of my dear father J.B. Gerard Michel.

ACKNOWLEDGMENTS

I am sincerely grateful to my major professor, Dr. Ramachandran P.K. Nair, for accepting me as his student and providing me valuable guidance and academic support. I am obliged to Dr. Vimala Nair, my co-advisor, for her important assistance and advice during the course of my research. My sincere appreciation goes to Dr. Jerry Sartain for his encouragement and dedicated help with the statistical analysis of my data. I would like to thank Dr. Johannes Scholberg and Dr. Michael Bannister for their encouragement and advice during my PhD studies.

Special thanks are extended to the study participants, Fred Clark (Alachua), Rudy Garber (Manatee), Bruce Goff (Suwannee), and Harris Hill (Osceola), without whom this study would have not been possible.

My appreciation also goes to several friends and collaborators for their assistance at various stages of this study, Dawn Lucas, Dr. Samuel Allen, Dr. Myrlene Chrysostome, the staff/students of the Soils Lab (SWSD, UF), Williams Reve (SWSD, UF), Solomon Haile (SFRC, UF), and Brian Roth (SFRC, UF).

None of this would have been possible without the moral support of my beloved wife, Daphnée B. Michel, my precious son Alain-Christian, and my dear mother, Germaine Delaquis Michel. My appreciation goes to my two sisters, Joyce Michel Dalpuppo and Abilene Michel Celestin, my uncle Jean-Claude Michel, and my godfather Ronald Maximilien, for their encouragement throughout my graduate studies. Finally, I wish to express my gratitude to the team of the Center for Subtropical Agroforestry.

I would like to acknowledge USDA IFAFS/CSREES (Initiative for Future Agricultural and Food Systems grant through the Center for Subtropical Agroforestry (CSTAF), University of Florida) for supporting this study.

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December 2006

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Phosphorus (P) and nitrate-nitrogen (N) loss from sandy soils that are predominant in the 1.4 million ha of pastureland in Florida is a major cause of water pollution. We hypothesized that soil P and N loss would be lower from silvopastoral systems than from treeless pastures because soil P and N removal by the combined stand of trees and pasture would be more than that of treeless pasture. Four slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) silvopastoral systems located respectively in Osceola, Manatee, Suwannee, and Alachua counties in Florida were selected. The Manatee and Osceola soils are Spodosols, and the Alachua and Suwannee soils are Ultisols. Soil samples were collected depth-wise from 0 to 100 cm. Soil P storage capacity (SPSC), the maximum amount of P that can be safely applied to a soil before it becomes an environmental concern, was calculated. Water-soluble P concentrations in the 0 – 5 cm soil layer were 4 and 10 mg kg^{-1} for the silvopasture and treeless pasture in Suwannee, 11 and 23 mg kg^{-1} in Manatee, 7 and 11 mg kg^{-1} in Osceola and in 6 and 11 mg kg^{-1} in Alachua. Total SPSC

in the upper one meter depth were 342 and -60 kg ha^{-1} respectively in the silvopasture and treeless pasture in Suwannee. The corresponding values were 329 and 191 kg ha^{-1} in Manatee, 657 and 926 kg ha^{-1} in Osceola, and -36 and -542 kg ha^{-1} in Alachua. The results suggest that P buildup within the soil profile was less in silvopastures than in treeless pastures. Therefore silvopasture systems can be expected to provide a greater environmental service in regard to water quality protection compared to treeless pastures under comparable ecological settings. In a related investigation, the single point isotherm method seemed to better estimate SPSC compared to the Mehlich-1 method. Although N followed similar trends differences between the two pasture systems were less conspicuous. This may be related to the difficulties in monitoring N, which is more labile than P; the highly dynamic soil nitrogen levels might have confounded the results.

CHAPTER 1
INTRODUCTION

Background

Phosphorus (P) and nitrogen (N) are critical to all forms of plant life. Nitrogen is an essential component of basic biological building blocks such as amino acids and thus their polymers: peptides and proteins. Nitrate-N, a negatively charged ion, is not adsorbed by the negatively charged colloids that dominate most soils (Brady and Weil, 2002). As a result, it is susceptible to off-site losses via deep leaching (the downward movement of nutrient below the effective root zone with percolating water) or in runoff (overland and lateral subsurface flows). Nitrates (as in fertilizers) are highly soluble in water and therefore move readily via leaching or runoff into the groundwater below. According to Yadav (1997), 68% of $N0_3$-N accumulation occurred outside the crop-rooting zone and 20% of nitrate-N accumulation in the crop-root zone in the soil profile moved into groundwater annually. Nitrate concentrations above 10 mg L^{-1} in drinking water may lead to the "blue baby syndrome" (United States Environmental Protection Agency [USEPA], 2006).

Phosphorus is involved in many vital functions in plants such as energy storage and transfer, photosynthesis, respiration, protein and nucleic acid synthesis, and ion transport across cell membranes. Fertilization of crops represents the largest proportion of P used in agriculture (Wood, 1998). Phosphorus and nitrogen fertilizers consumption in the U.S. for 1960 to 2003 is shown in Figure 1-1(United States Department of Agriculture/Economic Research Service [USDA/ERS], 2006a).

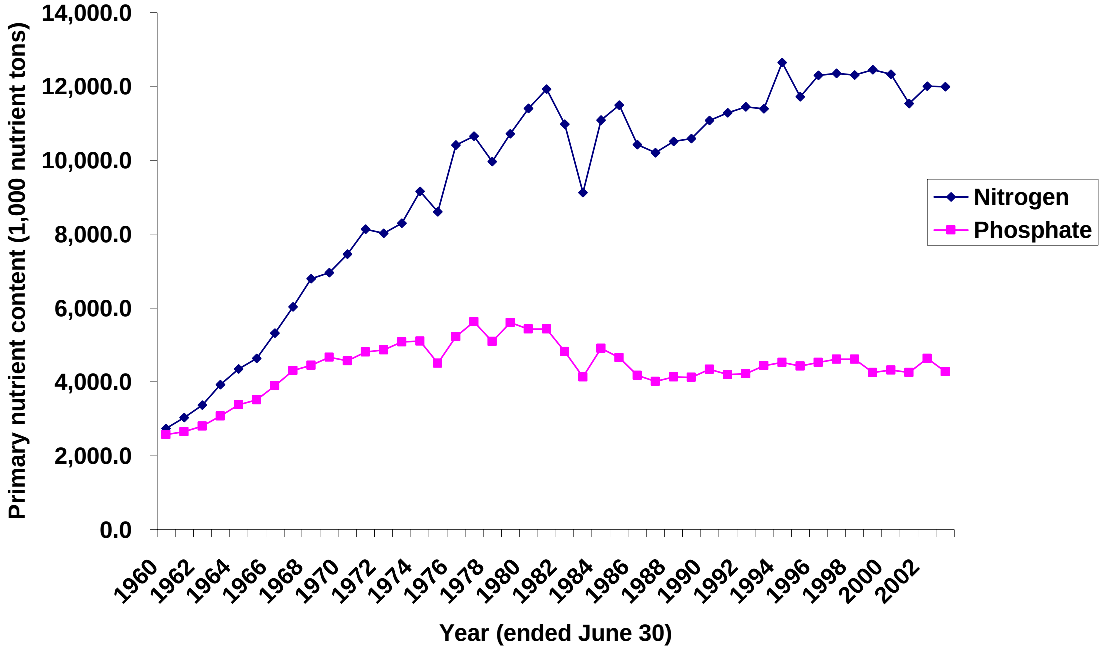

Figure 1-1. U.S. consumption of nitrogen and phosphate for 1960-2003. Sources: USDA/ERS (U.S. Department of Agriculture / Economic Research Service), 2006a.

In areas of intensive crop and livestock production, continual P applications as mineral fertilizer and manure in excess of crop removal rates often result in P accumulation (Sharpley et al., 1994; Tiessen, 1995). Phosphorus exists in agricultural fields either in a dissolved form or as attached to soil particles. Phosphorus is often the most limiting nutrient in surface water systems, and even small additions of P can have a great influence on primary production in these waters (Correll, 1998). Concern about the environmental fate of P has arisen from the evidence that land-applied animal wastes and fertilizers can potentially promote eutrophication of water bodies (Allen, 1987; Breeuwsma and Silva, 1992; Lemunyon and Daniels, 1997; Correll, 1998; Parry, 1998). Phosphorus concentration above 0.02 mg L^{-1} in lake water may result in increased alagal growth in P-limited systems. Excessive algae growth will decrease dissolved oxygen levels and reduced water transparency. This process is referred to as eutrophication (Sharpley et al., 1999), and is directly associated with nutrient enrichment of surface waters. Thus, even if P losses from agriculture were small from an agronomic point of view, they may still constitute a serious potential environmental problem. Reducing excess loadings of P and NO_3-N into both surface- and ground-water is an important environmental goal in the southeastern USA.

Problem Statement

Improved nutrient management strategies are required to maximize plant uptake of nutrients and thus minimize potential losses by runoff and leaching in order to maintain surface and ground water quality. The role of agroforestry systems, especially the effect of trees within agroecosystems, on nutrient retention and/or soil storage is therefore of interest. Due to their deep rooting systems, trees may provide a mechanism for improved nutrient capture, by which tree-based systems act as a "safety net" for capturing nitrates and other nutrients that would otherwise leach below the root zone of agronomic crops (van Noordwijk et al., 1996; Rowe et al., 1999). Although this has been demonstrated in tropical agroforestry systems (Seyfried and Rao, 1991; Horst 1995; Young, 1997; Lehmann et al., 1999; Rowe et al. 1999; van Noordwijk et al., 1999; Rowe et al., 2005), such nutrient movement studies in temperate agroforestry systems are rare, and whatever little that has been done has focused on riparian buffers. Nevertheless, these few studies have demonstrated the effectiveness of riparian buffer systems in reducing non-point source pollution and thereby improving water quality (Schultz et al. 2000; Schultz et al. 2004). Little information is available on the environmental implications of other agroforestry practices such as silvopasture in regard to their impact on surface and groundwater quality.

Silvopasture, in the North American and other temperate-zone context, refers to intentional combination of trees, forage plants and livestock into an integrated, intensively-managed system (Nair, 1993; Garrett et al., 2000; Nair et al., 2004); trees in such systems are managed for high-value sawlogs and at the same time an annual income is generated from livestock grazing. Silvopasture is considered to be the most promising agroforestry practice in the southeastern United States (Workman and Allen, 2004). According to Zinkhan and Mercer (1997), silvopasture is the most common form of agroforestry in the southern United States. Studies from across the southern pine region (Louisiana, Mississippi, and Georgia) report the possibility of productive livestock grazing while maintaining, or even improving, high value timber production (Workman and Allen, 2004).

With the realization about its environmental amelioration potential and greater appreciation of the societal value of ecosystem benefits such as carbon sequestration and also providing unique wildlife habitats, the practice of silvopasture is now receiving increased interest as an innovative and viable strategy for agroecosystem management (Nair et al., 2005). Based on this, the focus of this study will be on the role of silvopastoral systems in reducing P and N losses from the soil.

Organization of the Dissertation

The research is presented in five chapters. Chapter 2 is a review of the current literature on agroforestry and silvopasture in the U.S. and Florida. This chapter outlines the problems associated with land-use changes and their environmental impacts in Florida, and discusses the development of new concepts of P management. Chapter 3 presents the main characteristics of the study sites in Florida in terms of the soil chemical and physical characteristics as well as the plant species found in the two pasture systems (treeless pasture and silvopasture). It also includes a detailed account of the soil sampling methodology used in the study. Chapter 4 contains the results of the attempt to test the safety net hypothesis by measuring the soil phosphorus and nitrate-N concentrations throughout the soil profile for both the silvopasture and the treeless pasture sites at four locations in Florida and for two representative soil orders (Spodosols and Ultisols). An analysis of the "remaining soil P storage capacity" of the study sites at the four locations with comparison between the treeless pastures and the silvopastures in the two soil orders is the subject of Chapter 5. The final chapter (Chapter 6) includes the synthesis and conclusion of the results and is followed by recommendations for future research needs.

Hypothesis and Objectives

The overall hypothesis of the study is that the presence of trees in silvopastoral systems would enhance soil nutrient retention and/or crop removal of P and nitrates compared to treeless pastures and thereby reduce potential loadings rates of surface waters.

The study objectives are to

(i.) Quantify water soluble P (WSP), Mehlich-1 P, and NO_3^- and NH_4^+ in the surface and subsoil horizons in manure-impacted soil profiles of silvopastoral and treeless pasture systems at four different locations (two soil orders) in Florida;

(ii.) Determine the relation between WSP and P saturation ratio (PSR_{M1}) in the surface and subsoil horizons of the four study sites;

(iii.) Estimate the remaining soil P storage capacity (SPSC) of the two pasture systems sites at the four locations;

(iv.) Assess differences in SPSC estimates by comparing two methods (Mehlich-1 and single-point isotherm).

CHAPTER 2
REVIEW OF LITERATURE

Agroforestry and Silvopasture

Historical Development of Agroforestry in the U.S. and Florida

Drastic changes have occurred in land-cover use during the past 150 years in the Eastern United States. Forests, woodlands and grasslands were severely affected by land clearing for timber exploitation and agriculture from the middle 1800s to the 1930s (Ware, 2002). Between 1973 and 2000, land cover statistics showed that forests remained the predominant cover, despite the decline from a high of 28.5 % in 1973 to a low of 24.3 % in 2000. Agriculture saw a similar decline from 10.8 % to 8.0 % during the same period (U.S Geological Survey [USGS], 2006).

Today, crop, pasture lands and woodlands represent 3.9, 4.0, and 3.4 millions hectares, respectively, in Florida, Georgia, and Alabama (USDA/ERS, 2006b). Agriculture and forestry combined represent the most important economic activity in the states of Alabama and Georgia and the second (only to tourism) in Florida. In spite of this dominant role of agriculture and forestry, substantial population growth has occurred, causing an expansion of urban and developed land. Between 1970 and 2000, the population of Florida increased by 235 percent, from 6.8 million to 16.0 million people (NPG, 2006). At present, the State of Florida has over 17 million residents (Florida Division of Emergency Management [FDEM], 2006). The urbanization of rural lands and the subsequent increase in land prices constitute a striking testimony of the development of suburbs and cities across rural areas of America. The main consequence of urbanization is the diversion of food producing lands or lands reserved for forests and natural habitats, to accommodate expanding populations (Cordell et al., 1998). Agricultural intensification of croplands, forest and livestock systems has been very articulated during recent decades. The mid-1900s brought about an unprecedented increase in food and fiber yields per unit area resulting from a steady increase in the use of chemical fertilizer, pesticides and irrigation while a decline in the rate of land clearing was observed (Workman and Allen, 2004). By the 1970s, row crops generated production surplus and higher incomes for farmers. During the 1980s, intense mechanization and farm inputs augmented the number of farm loans, which led to an increase in farm debt and eventual large-scale loss of farms to foreclosures (Fitchen, 1991). Today, excessive input costs and low profit margins resulting from strong competition from corporate-run farms and inexpensive foreign products are driving small farms to abandon farming activities (Workman and Allen, 2004). Concerns regarding the effects of large-scale transformation of ecosystems on the natural structure and function of land and water resources have been raised and continue to be important research and development issues (Lappé et al., 1998; Vitousek et al., 1997; Sampson and Hair, 1990; Savory, 1988).

A decline in industrial timberland acreage of more than 0.5 million hectares has been observed in Florida and Georgia, since 1989 (Workman and Allen, 2004). Much of this timberland is now owned by private corporations that are expected to carry on a management plan for wood products (Conner and Hartsell, 2002). As urbanization follows its course and an increasing number of people desire recreations in natural settings, there will be a growing need for trees both within and outside forests (Long and Nair, 1999; Leakey, 1998).

With an increase in population growth rate in the southern states and a decline in industrial timberland, there have been growing concerns about the environmental problems associated with potential fertilizers and pesticides pollution, soil erosion, pest problems, and loss of biological diversity. Consequently, there is increased interest in the use and adoption of land-management practices that increase both the aesthetic and recreational value of lands while protecting and conserving the natural resource base (Bliss et al., 1997; Teasley et al., 1997). Agroforestry, the intentional growing of trees with crops, pasture and/or livestock, affords farmers with an alternative land-use practice with potential for mitigating some of the environmental and economic setbacks associated with modern agriculture (Nair, 1993). Agroforestry is now receiving increased attention from researchers, landowners, government and private agencies in North America (World Agroforestry Centre [ICRAF], 2000; Lassoie and Buck, 2000; Garrett et al., 2000).

An essential characteristic of agroforestry is the wide array of land-management options it offers for preserving natural resources and generating additional income. Agroforestry systems, via the integration of trees with crops and/or livestock on the same land, could provide numerous environmental services. These services include reduction of soil erosion and nutrient losses, enhancement of inherent soil fertility, water infiltration and groundwater recharge, protection against wind, snow, noise, and odor and other nuisances, and creation of attractive and healthier landscapes (Ewel, 1999; Jordan, 1998, Daily, 1997; Leakey, 1996). By diversifying the farm enterprises, agroforestry can also help landowners to improve the resilience of their system and to minimize risks associated with income loss from price fluctuation, crop failure or other unexpected problems. Opportunities for intensifying the use of agroforestry practices, and the benefits that result, are gradually rising in the southern U.S. (Workman and Allen, 2004).

Agroforestry in the Southeastern U.S. can be divided into five major practices or land-use techniques (Merwin, 1997; Garrett et al., 2000; Nair, 2001): Alley Cropping, Forest Farming, Riparian Forest Buffers, Silvopasture, and Windbreaks (Table 2-1).

Table 2-1. Agroforestry practices in the Southeastern U.S.

Silvopasture	Silvopasture is the intentional combination of trees, forage plants and livestock together as an integrated, intensively-managed system. Silvopasture can provide profitable opportunities for softwood or hardwood timber growers, forest landowners, and livestock producers.
Alley cropping	Alley cropping is the cultivation of food, forage or specialty crops between rows of trees. It is a larger version of intercropping or companion planting conducted over a longer time scale. Alley cropping can provide profitable opportunities for row crop farmers, hardwood timber growers, nut growers and Christmas tree growers.
Riparian Forest Buffers	Riparian forest buffers are strips of trees, shrubs and grass planted between cropland or pasture and surface water courses. Buffers protect water quality, reduce erosion and flooding. Riparian forest buffers can provide beneficial opportunities for row crop farmers, ranchers, horticulturists, and dairy and livestock producers.
Forest Farming	Forest farming is the intentional cultivation of edible, medicinal or decorative specialty crops beneath native or planted woodlands that are managed for both wood and understory crop production. It does not include the gathering of naturally-occurring plants from native forests, also known as wildcrafting. Forest farming can provide profitable opportunities for forest and woodland owners, nut growers, sugar maple growers, and herb growers.
Windbreaks	Windbreaks are linear plantings of trees and shrubs designed to enhance crop production, protect people and livestock, and benefit soil and water conservation. Windbreaks can provide valuable opportunities for vine and tree fruit growers, row crop farmers, livestock producers, and rural homeowners.

Source: AFTA (2006)

Silvopasture: History, Characteristics and Potential

Grazing in pine (*Pinus* spp.) forests in the Lower Costal Southern United States dates back to around 1520, when cattle were first introduced in Florida by Ponce de Leon from Spain (Lewis, 1983). In the early 1950s, pine trees were first planted in improved pastures as part of the Conservation Reserve Soil Bank Program (Nowak and Long, 2003). At present silvopasture is becoming increasingly attractive to non-industrial private forest landowners and livestock operators in southeastern United States who want to diversify their enterprise (Nair et al., 2005).

Silvopasture has historically included use of shade trees in pasture grazed orchards or woodlands, and as rangelands that include a managed tree or shrub component (Clason and Sharrow, 2000; Robinson and Clason, 1997; Williams et al., 1997). In the Southeast, silvopasture has generally included forest grazing with cattle, such as flatwoods rangeland (Pearson, 1997), pine managed for turpentine and sawlogs mixed with forage systems (Byrd et al., 1984; Cary, 1928), and tree pasture practices with pecan *(Carya illinoensis* K. Koch) (Reid, 1991). Silvopastoral systems integrating tree, forage and livestock production are the most common agroforestry practices found in the United States and Canada with the largest area of grazed forests occurring in the southern and southeastern United States (Clason and Sharrow, 2000). Burton and Scarfe (1991) suggested associations with goats for both meat production and vegetation management. According to Lewis and co-workers (Hart et al., 1970) the association of southern pine production and beef cattle with improved pastures constitutes an opportunity for the production of multiple products. Increased economic benefits may result from the integration of forestry with ranching by helping buffer year-to-year income fluctuation through the sale of forest products and hunting leases generated by the creation of wildlife habitat. Studies on silvopasture in the Southeastern United States have reported the economical viability of such enterprise (Lundgren et al., 1983; Clason, 1995; Grado et al., 2001; Stainback and Alavalapati, 2004; Alavalapati et al., 2004). According to Stainback et al. (2004), the combination of slash pine (*Pinus elliotii*) with cattle production could become competitive with conventional ranching in Florida when environmental costs and benefits are considered in the analysis.

Research on warm season forage under pines in South Georgia (that began in the 1940s) showed that Pensacola bahiagrass (*Paspalum notatum)* as the most shade tolerant of the 23 grasses studied (Lewis and Pearson, 1987; Pearson, 1975). Several legume species have been recognized as having promising potential for production under partial shade (McGraw et al., 2001). In a silvopasture study comparing a double row system of pines (3.1m between rows and 1.2 m between trees and 12.2 m wide alleys) to a single row system (3.1 m x 3.7 m), the double row system yielded more forage and as much wood (Lewis et al., 1985). At present the double row system remains the most popular spacing for silvopasture across the region (Clason and Sharrow, 2000). Recently developed varieties of bahiagrass, such as Tifton-9 and Argentine may perform as better warm season forage component in silvopasture systems (Nowak and Blount, 2002). Clason (1995) reported higher internal rate of return in silvopastoral practice (13%) than managed timber (9%) or open pasture (6%) in the state of Louisiana. Grado et al. (2001) reported that both silvopasture and pasture had positive cash flows with that for pasture being highest during a short evaluation period. In Georgia, pine growth improved with controlled grazing (Lewis et al., 1985), and loblolly-cattle-forage systems in the Coastal Plain may have a 70% greater net present value per unit area (Dangerfield and Harwell,

1990) than a pure forestry operation . It has been demonstrated in Alabama that when mimosa (*Albizia julibrissin*) and leucaena (*Leucaena leucocephala*) are grown without fertilizers, they can be cut for fodder at 6 to 8-week intervals (Bransby et al., 1996). A livestock-forage-Christmas tree production system could be another viable silvopasture mixture (Pearson et al., 1990). According to McGowan et al. (1999), there is also a growing interest in goat production in this region. In the South, forest industry has used goats as an alternative to using chemical or mechanical means of weed control in pine plantations (Solaiman and Hill, 1991). Studies conducted in Arkansas and Alabama suggest that goats can play a key role in vegetation reduction, especially kudzu (*Pueraria lobata*), during site preparation for pine plantations (Pearson and Martin, 1991; Bonsi et al., 1991).

Environmental Quality and Land Use Systems

Florida Soils and their Management

Florida soils are characterized by coarse soil textures and acidic conditions. P loading of surface and ground waters following transport from dairy operations and heavily manured pasturelands in these porous soils by P-rich animal manures constitute a serious environmental concern .The Florida Phosphorus Index, a field-based indexing system developed to rank the vulnerability level of farmlands as sources of P loss in surface runoff water (University of Florida/Institute of Food and Agricultural Sciences [UF/IFAS], 2006), take into account both phosphorus transport characteristics and management practices. Management factors include soil test P, P application method, and source and rate of P application (Nair and Graetz, 2004). Phosphorus based manure applications are being increasingly incorporated into farm nutrient planning program (Sharpley et al., 2004) because nitrogen-based manure applications have resulted in continuous P-accumulation in soils. According to Sharpley et al. (2004), the planning includes “the selection, timing, and implementation of source and transport best management practices at field, farm, and watershed scales”.

Some of the practices used for controlling erosion and runoff (the transport factor) include, conservation tillage, contour farming, constructed wetlands, and vegetative filter strips. Conservation tillage is a management practice that provides efficient and effective erosion control and it can improve soil properties and soil quality (United States Department of Agriculture/Natural Resources Conservation Service [USDA/NRCS], 1999).This practice can improve soil structure thereby resulting in higher infiltration and percolation rates, increased water holding capacity and, enhanced resistance to erosion. Vegetative filter stripes are narrow rows of permanent vegetation (usually grasses or shrubs) planted on the contour can be used to slow down runoff, trap sediment, and eventually build up “ natural or living” terraces (Brady and Weil, 2002). Constructed wetlands (CW) have been used for decades for the treatment of domestic (Kadlec, 1985) and industrial wastewaters and agricultural runoff (Higgins et al., 1993). These systems are useful for reducing suspended solids, ammonium-N, P, biochemical oxygen demand and chemical oxygen demand in sewage (Tanner et al., 1995 and Von Felde and Kunst, 1997).

Measures aimed at regulating the P accumulation involve attaining a suitable balance between P imports and exports. Suitable management practices may include, composting, improved livestock feeding, suitable rate, method, and timing of land application of manure, along with physical and chemical treatments of manure (Chrysostome, 2005). Drinking water treatment residuals (WTRs), non-hazardous materials that are obtained at no costs from drinking-water treatment plants (Makris et al., 2005), offer a cost-effective chemical soil amendment of P-impacted soils. These materials reduce soluble P in soils with low P-sorption capacities, without affecting soil fertility (Codling et al., 2002). Similar findings have also been reported by Novak and Watts (2005).

Fertilizer Use and Non-Point Source Pollution

The U.S. Environmental Protection Agency (EPA, 1996) has identified agricultural non-point source pollution as the major cause of stream and lake contamination that prevents the attainment of the water quality goals established in the Clean Water Act. The southeastern U.S. is home to a vast number of water bodies; Florida alone has over 7,800 lakes, about 10,000 km^2 (4,000 sq. miles) of estuaries, and over 80,000 km (50,000 miles) of rivers and streams, including major water bodies such as Lake George, Lake Okeechobee, the Everglades, and the St. Johns and Kissimmee rivers (Florida Department of Environmental Protection [FDEP], 2003). In addition, the Floridian aquifer system, underlying almost all of Florida and portions of Alabama, Georgia and South Carolina, occupies a total area of about 260,000 km^2 (100,000 sq. miles), and supplies over 11.4 billion liters (3 billion gallons) of water per day for all uses throughout the region (Johnson and Bush, 2002). There is increased awareness of non-point source pollution of waters from agricultural chemicals in drainage and runoff water (Tiessen, 1995). This issue is particularly important in Florida and surrounding areas, as the karst geography of the region is shaped by vast groundwater reserves that are sensitive to nutrient build-up, and has led to a growing demand for information regarding the impact of different land-use systems on surface water quality. Most of the common nitrogen and phosphorus fertilizers are water-soluble. In the high rainfall areas, especially on sandy soils, these nutrients can be leached into the groundwater and washed into waterways, even after short periods (months and years, rather than decades) (Summers, 2002). In the U.S., only 18% of the N-fertilizer inputs leaves farms with the produced crop, meaning that on average, 174 kg ha^{-1} of surplus N is left behind in croplands each year (Ecological Society of America [ESA], 1998). Animal manures and fertilizers, pose a serious threat to surface and groundwater quality in major river (Suwannee River and Lake Okeechobee) basins of Florida. Elevated NO_3-N concentrations have been measured in water from both domestic and monitoring wells in the Suwannee River Basin (Katz et al., 1999), exceeding the maximum contaminant level of 10 mg L^{-1} set by the U.S. Environmental Protection Agency. Nitrate-N concentrations above this limit can cause methemoglobinemia or "blue baby" syndrome in infants and elderly adults (Mueller and Helsel, 1996). These increased nitrate concentrations in these waters have been attributed to dairy wastes (Andrews 1994), poultry operations (Hatzell, 1995), and excessively high fertilizer applications (Katz et al., 1999).

Soil Phosphorus as a Pollutant

In most U.S. watersheds, P export occurs mainly in surface runoff rather than in subsurface flow. On the other hand, in some regions, particularly the Gulf coastal plains and Florida, as well as in fields with subsurface drains, P can be transported in drainage waters (Sharpley et al., 1999). Soils with high water infiltration rates and low nutrient retention capacity, such as sandy soils and soils with low activity clays and low organic matter content, are particularly prone to nutrient leaching (Lehmann and Schroth, 2003). The Spodosols of Florida receiving significant loadings of animal manure, on the other hand, are more prone to subsurface leaching of P (Nair and Graetz, 2002). The P in organic manures has been shown to be more susceptible to leaching than that in inorganic fertilizers (Eghball et al., 1996), and P leaching from grazed grassland tends to increase when the stocking density is high, possibly due to a greater amount of soluble organic P being released from dung (Beauchemin et al., 1999). The injection of manure slurry also greatly increases the leaching of P (Tunney et al., 1997). Phosphorus transported from agricultural soils can accelerate eutrophication (Sharpley et al., 1994). This phenomenon leads to increased costs and difficulty of water purification for drinking purposes (to remove odor, turbidity, and color) and the replacement of high quality edible fish, submerged macrophytic vegetation, and benthic organisms with coarse, rapid-growing fish and algae, along with the control of proliferating noxious aquatic plants.

Nutrient Management in Silvopasture

Nutrient Cycling in Agroforestry Systems

Research conducted in tropical agroforestry systems has demonstrated the potential for nutrients cycling by deep-rooting trees. According to Kang (1997), the presence of woody species in an alley cropping production system has been shown "to contribute to (1) nutrient recycling, (2) reduction in soil nutrient leaching losses, (3) stimulation of higher soil faunal activities, (4) soil erosion control, (5) soil fertility improvement and (6) sustained levels of crop production". Horst (1995) reported lower nitrate concentrations in the soil solution and consequently reduced leaching under hedgerow intercropping with *Leucaena leucocephala* and annual food crops than in the agricultural control treatments in southern Benin. Lehmann et al. (1999) measured lower nutrient leaching under an *Acacia saligna*- sorghum (Sorghum *bicolor*) intercrop than under pure sorghum with runoff irrigation in northern Kenya. Das and Chaturved (2005) studied nutrient concentrations in plant and soil and their corresponding cycling rates of cycling in poplar (*Populus deltoides*)-based agroforestry systems at Pusa, Bihar, India. The authors concluded that the poplar-based agroforestry system was more sustainable than other single-crop systems in terms of in terms of soil nutrient status. A study conducted by Tapia-Coral et al. (2005) in Central Amazonia, Brazil showed that the litter of the agroforestry systems had lower carbon: nutrient ratios than the litter in the secondary forest control, indicating a faster nutrient recycling in the agroforestry systems. Manezes et al. (2002) found that the preservation of native trees or introduction of exotic tree species in *Cenchrus ciliaris* pastures in semiarid northeastern Brazil significantly affects microclimate and the dynamics of litter and soil nutrients, and may contribute to enhanced nutrient cycling in these systems.

Other studies conducted in temperate settings have also shown similar results. In a pecan (*Carya illinoensis*)–cotton (*Gossypium hirsutum*) alley cropping system in northwestern Florida, Allen et al. (2004) found that N-leaching rates were lower in a 'non-barrier treatment' (competition treatment) compared to a 'barrier' (competition-reduced treatment) treatment. Cumulative nitrate leaching below the 0.3 and 09 m depth were 64 and 13 kg ha^{-1} for non-barrier treatment, compared to 122 and 46 kg ha^{-1} for respective depths in barrier treatment. It appears that the tree roots captured N in the non-barrier treatment, resulting in lower leaching rates below the root zone of the cotton crop. Furthermore, tree water uptake, in addition to cotton water uptake in the non-barrier treatment, may have decreased overall water drainage in comparison to the barrier treatment, thereby influencing nutrient loadings rates. In the same study Allen et al. (2004) reported a greater nitrification and mineralization rates in no-barrier treatment than in a barrier treatment due to higher soil N, resulting from reduced nutrient uptake by cotton. Udawatta et al. (2002) found in a paired watershed study conducted in northeastern Missouri, consisting of agroforestry (trees plus grass buffer strips), contour strips (grass buffer strips), and control treatments with a corn (*Zea mays*)–soybean [*Glycine max*] rotation, that nitrate-N loss was reduced 24 and 37% by contour strip and agroforestry treatments. Corresponding treatments also reduced total P loss by 8 and 17% on contour strip and agroforestry watersheds.

Soil Phosphorus in Pasturelands

Pasturelands in Florida receiving significant load of manure are subject to subsurface leaching of phosphorus due to the sandy nature of the soils. Many P compounds present in manure are water soluble to begin with and have a potential to move with rain or irrigation water (Gerritse, 1977). Furthermore, animals are known to utilize P inefficiently in feed (only 30% is retained); therefore most of the P entering livestock operations end up in manure (Sharpley and Moyer, 2000). In many areas of concentrated animal production, manures are generally applied based on the crop N-requirements to avoid groundwater quality problems associated with leaching of excess N. This frequently leads to P build up in excess of the sufficiency level for optimal crop yields, which in turn can enhance the potential P runoff and leaching (Haygarth et al., 1998; Heckrath et al., 1995; Sharpley et al., 1996). With time, the organic P will be absorbed or hydrolyzed to form inorganic phosphate-containing compounds, which may be subject to leaching and run-off as soluble P compounds (Zublena, 1995). Hedley et al. (1982) found that the major portion of manure P was soluble in weak extractants such as water and bicarbonate. Sharpley and Moyer (2000) assessed phosphorus forms in manure for dairy, poultry and swine and P leaching potential using a simulated rainfall. Inorganic P in the manures accounted for 63 to 92% of total P. Phosphorus leaching from the different manures by simulated rainfall showed a close relationship to water soluble P concentration. According to Sharpley et al. (2004), there is a general shift in soil P chemistry with the application of manure from Fe-P and Al-P to Ca-P compounds, resulting in a relatively greater extraction of P by the Mehlich-3 but a lower water extractability of soil P. This shift has important environmental implications for soil P testing. For example, the fact that Mehlich-3 P has been shown to overestimate potential for P-losses in surface flow from heavily manured soils could be explained by the extraction of Ca-P minerals that are insoluble in water.

New Concepts of P Management

Soil test P (STP) is the most widely used means to estimate the potential risk for P leaching fom the soil (Maguire and Sims, 2002). Diagnostic soil test P values were initially developed to evaluate the probability of obtaining a positive crop response to the addition of a P fertilizer. However, it was not intended to be used as an environmental indicator of the potential risk of P pollution. According to Sharpley et al. (1999), additional calibration (beyond that conducted for fertility recommendations) are required in order to also validate soil-test P values as an environmental indicator. Calibration studies have resulted in development of environmentally-based threshold STP concentrations and have been established for several regions. Sharpley and Tunney (2000) have presented an array of examples of the use of such tests as guides for P management recommendations to protect water quality. Heckrath et al. (1995) found that P leaching losses were low when P extractable in 0.5 M sodium bicarbonate (Olsen-P) was less than 60 mg kg^{-1} and then increased rapidly when Olsen-P exceeded 60 mg kg^{-1}. They referred to this value as a change-point, above which the potential for P loss through leaching increased considerably. However, the change-point value was found to be affected by experimental conditions, such as the range of STP values tested and the soil to solution ratio for the P desorption parameter (Koopmans et al., 2002). Börling (2003) presented evidence that even if a change-point can be identified, it would be site-specific. Hesketh and Brookes (2000) determined change-points in seven soils and found variation from 10 to 119 mg kg^{-1} Olsen-P.

Water soluble P is another environmental soil testing parameter for assessing potential P losses. Phosphorus extracted from soils using distilled deionized water (WSP) is expected to simulate the rapid release of P to water better than a stronger chemical extractant (such as agronomic soil P tests), since rainfall is very similar to distilled water (Moore et al., 1998). This extraction should also maintain the soil pH within one unit of its original value, which is a desirable attribute since P solubility is highly dependent upon soil pH (Golterman, 1998; Sharpley, 1993). Pote et al., (1996) demonstrated, in a field study with tall fescue the existence of a strong correlation between water soluble P with runoff P.

The concept of Degree of Phosphorus Saturation (DPS), was developed in the Netherlands (van der Zee et al., 1987; Breeuwsma and Silva, 1992) and later applied in other parts of the world has been used to evaluate the risk of P leaching from soils as follows:

$$\mathrm{DPS} = \frac{\text{Sorbed P}}{\text{P sorption capacity}} \times 100$$

The DPS estimates how close the soil is to saturation and facilitates comparison among soils with varying P sorption capacities. Different methods of estimating sorbed P and P sorption capacity can be used to determine DPS. In the Netherlands and several other countries, P extracted with ammonium oxalate has been used to estimate sorbed P, and soil concentrations of both Fe and Al in order to estimate P sorption capacity (Börling, 2003) as follows:

$$DPS = \frac{P_{ox}}{(Fe_{ox} + Al_{ox})\alpha} x100$$

where α is an empirically derived sorption coefficient which has a value between 0 and 1. This coefficient is derived from the following relationship

$$P \text{ sorption capacity} = (Fe_{ox} + Al_{ox})\alpha$$

A value for α of 0.5 was recommended by Beauchemin and Simard (1999); Breeuwsma and Silva, 1992; Koopmans et al., 2003; Schoumans and Groenendijk, 2000 and Sims et al., 2002 while Nair and Graetz (2002) reported a value of 0.55 for Spodosols in Florida. The DPS normalizes P (oxalate, Mehlich-1 or -3) to extractable Fe and Al, and has been related regionally to soil solution P concentration (Nair and Harris, 2004). Hooda et al. (2000) suggested that the DPS, which relates ammonium oxalate-extractable P to the sum of oxalate extractable Fe and Al (DPS_{Ox}), is a good indicator of the soil's potential to release P. Other researchers have suggested that DPS_{Ox} can be a suitable tool for predicting subsurface P lost since it has been shown to be closely correlated to P concentrations in leachate waters (Leinweber et al., 1999 and Maguire and Sims, 2002).

A soil is P-saturated when 25% or more of PSC (Phosphorus Sorption Capacity) has been used. This level of P sorption saturation will likely result in ground water P concentrations above the 0.1 mg P L^{-1} standard used in the Netherlands (Breeuwsma et al., 1995). Other studies conducted by Maguire et al. (1998) and McDowell and Sharpley (2001) have shown a low potential for P losses via leaching when DPS is <20 to 25% and sharp increase in P leaching above this DPS value. More recently, Nair and Graetz (2002) showed that DPS_{M1} can be used as indicator of soluble P for both surface A horizons and subsurface Bh (spodic horizons) of Spodosols in the Lake Okeechobee basin. Nair et al. (2004) taking into consideration the change points, confidence intervals, agronomic soil test values, and DPS values from other studies, recommended a threshold DPS_{M1} of 30% for Florida sands. Values for $DPS_{M1}$of 31 to 60% warrant caution with regard to further addition of P to a land-use system, while DPS_{M1} values of > 60% imply that the can potentially impair water quality. The Phosphorus Saturation Ratio (PSR) is similar to DPS, but does not use a corrective constant (α) associated with the original definition of DPS (Breeuwma and Silva, 1992).

When used as environmental indicators of off-farm P loss, both STP and DPS failed to provide a clear indication of the capacity of a soil to retain added P. Therefore, soils with very low STP values may nevertheless have insufficient capacity to retain added P, and soils with higher STP values may have capacity to retain additional P. Nair and Harris (2004) recommended the use of a DPS-based calculation of the remaining soil P storage capacity (SPSC) that consider risks arising from previous loading as well as inherently low P sorption capacity. The SPSC of a soil is based on a threshold PSR of 0.15: SPSC = (0.15 – PSR) x (Mehlich-1 Al + Mehlich-1 Fe) [Nair and Harris, 2004] where (Mehlich-1 Al + Mehlich-1 Fe) is proportional to the P sorption capacity of a given soil (van der Zee et al., 1987). According to Nair et al. (2004), the value of 0.15 used in the SPSC calculation is the best approximation available to date of the PSR value corresponding to the critical P solution concentration of 0.10 mg $litre^{-1}$ P as proposed by Breeuwsma and Silva (1992). The SPSC can be calculated by horizon (expressed as kg P m^{-3}) using the bulk density and the thickness of that horizon or by depth (expressed as mg P kg^{-1} or kg P ha^{-1}) [Nair and Harris, 2004]. The SPSC can be used for assessing the soil status in regards to future environmental risk-free P additions. In other words, the SPSC allows prediction of the amount of additional P that can be retained by a given soil horizon or depth before the added P becomes an environmental concern.

Silvopasture and Environmental Quality

Nutrient movement studies in temperate agroforestry systems are rare and whatever little that has been done has focused on riparian buffers. Nonetheless research undertaken on silvopasture in Florida has shown great promise. Preliminary research conducted on a silvopastoral site at a research farm at Ona, Florida, on flatwoods soils (Spodosols) suggest that silvopastoral sites are less likely to retain nutrients within the soil profile compared to an adjacent fertilized pasture with cattle grazing (Nair and Graetz, 2004) (Table2-2).

Table 2-2. Water soluble phosphorus (WSP) concentrations as affected by soil depth for a native flatwoods site, a silvopastoral site, and an adjacent treeless pasture at Ona, Florida, USA.[Q]

Depth	Native flatwoods	Silvopasture	Pasture
cm	WSP, mg kg^{-1}		
0-5	1.59 (1.14)[Q]	4.23 (1.34)	9.10 (3.26)
5-15	1.28 (1.17)	2.09 (1.36)	2.79 (2.20)
15-30	0.12 (0.02)	0.79 (0.39)	1.52 (0.94)
30-50	0.00 (0.00)	0.17 (0.14)	1.91 (1.25)
50-75	0.00 (0.00)	0.02 (0.02)	0.42 (0.40)
75-100	0.00 (0.00)	0.04 (0.03)	0.66 (0.52)

[Q]Source: Nair and Graetz, 2004
[Q]Numbers in parentheses are standard deviation values

In a study conducted at a University of Florida research station, Ona, Florida, for which long term information on the management history of the sites is available, Nair and Kalmbacher (2005), reported P concentrations in soil profiles obtained from each of the pasture sites to be in the following order: pasture>silvopasture>native pasture. In the same study the NH_4^+- and NO_3^--N concentrations were found to be higher in the surface horizon of the treeless pasture.

A substantial body of literature is available on the effectiveness of riparian buffers in reducing nutrient losses from farms to water bodies, and on the potential offered by these systems to reduce nutrient loss from agricultural lands. Hefting et al. (2005) reported that plant production, nitrogen uptake, and N retention were significantly higher in a forested buffer site compared to a herbaceous buffer site in riparian buffer zones in study conducted in six European countries. Results of a field monitoring study done in Tokachikawa watershed in Hokkaido, Japan, Cisadane, Cianten and Citamyang sub-watersheds in Indonesia and Cauvery watershed in southern India, all demonstrated the positive impact of forest buffer zones in reducing the influence of agricultural nutrients and chemicals on surface stream waters (Anbumozhi et al., 2005). In a study conducted in southern Illinois, USA, Blattel et al. (2005) found that ground water soluble P concentrations were significantly reduced by 14 percent in the first 1.5 m of both mixed hardwood forest and giant cane (*Arundinaria gigantea*) riparian buffers, and there was an overall 28 percent reduction in water soluble P concentration by 12 m from the field edge. Schoonover et al. (2005) showed that forest buffers significantly reduced incoming dissolved NO_3^--N, dissolved NH_4^+-N, total ammonium-N, and total orthophosphate concentrations in surface runoff within the 10.0 m riparian buffer by 97, 74, 68, and 78, respectively. Furthermore, overall nutrient reductions for giant cane buffer strips were 100 percent for all three nutrients due to relatively high infiltration rates. Finally, significant reductions of total NH_4^+- N and total orthophosphate were also detected at a distance of 3.3 m from the edge of the cane buffer compared to 6.6 m in the forest buffer. In a study conducted in North Queen Island, Australia, McKergow et al. (2004) reported a reduction in total N, total P and suspended sediment loads between 25 and 65% by the planar slope grass buffer and within the first 15 m of the moderately convergent grass buffer. Lee et al. (2003) showed, in a study in Bear Creek, Iowa, USA, that switchgrass buffer (*Panicum virgatum* cv. Cave-n-Rock) removed 95% of the sediment, 80% of the total-N, 62% of the nitrate-nitrate-N, 78% of the total-phosphorus, and 58% of the phosphorus, whereas a switchgrass/woody buffer removed 97% of the sediment, 94% of the total-N, 85% of the nitrate-N, 91% of the total-P, and 80% of the P in the runoff.

These findings provide clear evidence that agroforestry systems are effective in reducing the soil P and nitrate-N store and would therefore reduce the amount of nutrients likely to be lost from farmland. This phenomenon is of great importance because it presents a mechanism to sustain current agricultural land use while achieving both nutrient conservation and water quality protection.

CHAPTER 3
SOIL CHARACTERISTICS OF THE SILVOPSTURE AND TREELESS PASTURE STUDY SITES

Introduction

A thorough understanding of the distribution of nutrients in different soil layers is essential for developing effective nutrient management strategies that are economically viable and environmentally sound. From that point of view, this study was undertaken to investigate differences in soil characteristics between silvopasture and adjacent treeless pasture systems.

Materials and Methods

Seven of the twelve soil orders are represented in Florida (Collins, 2003): Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Spodosols, and Ultisols. The sites selected for this study represented two major soil orders of the state: Ultisols and Spodosols. Spodosols are characterized by having undergone soil processes that translocate organic matter and aluminum, or organic matter, aluminum, and iron, as amorphous materials (Collins, 2003). Spodosols occur mostly on coarse-textured, acid parent materials subject to ready leaching (Brady and Weil, 2002). The A and E horizons of Spodosols are sandy and have poor sorption capacities while the Bh (spodic) and the Bw horizons have much greater affinities for P retention (Mansell et al., 1991). According to Soil Survey Staff (1996), Spodosols are characterized by a highly fluctuating water table situated between the Bh and the A horizons during the summer rainy season, while it may go down to 125 cm during drier months. Due to low hydraulic conductivity of the lower soil layers, rainfall that penetrates the soil during high water table conditions tends to move laterally, transporting P to surface drainage ditches (Burgoa et al., 1991; Mansell et al., 1991). Approximately 3.4 million hectares in Florida have been mapped as Spodosols (Collins, 2003).

Ultisols are characterized by the presence of an argillic horizon, enough moisture for crops in most years, and a base saturation [proportion of chemical exchange sites on soil particles that are occupied by basic cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+})] less than 35 percent. They developed in relatively warm and moist climates, such as northwest Florida, and tend to be highly productive if managed properly. There are approximately 2.8 million known hectares of Ultisols (Collins, 2003) in Florida. The distribution of Ultisols and Spodosols in Florida is shown in Figure 3-1.

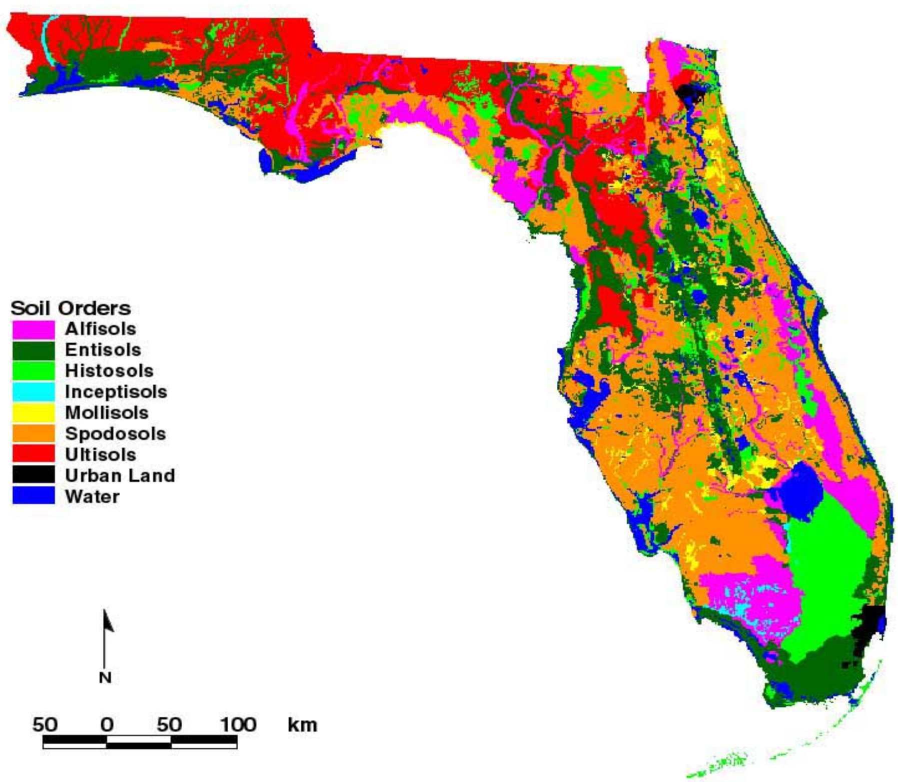

Figure 3-1. Soil orders of Florida (**Source: Collins (2001)**

Location of the Study Sites

The study was conducted on four farms that practice silvopasture in Florida: Mr. Harris Hill’s farm in Osceola County, Dr. Rudy Garber’s farm in Manatee County, the Florida Sheriffs Youth Ranch in Suwannee County, and Mr. Fred Clark’s farm in Alachua County (Table 3-1 and Figure3-1). The silvopastures consisted of a combination of slash pine (*Pinus elliottii*) and bahiagrass (*Paspalum notatum*), and the treeless pastures consist of bahiagrass (Figures 3-3 and 3-4). The tree planting configuration of the silvopastures in Osceola and Manatee locations was a double row planting (3.1 m between rows and 1.2 m between trees and 12.2 m wide alleys), whereas in Suwannee and Alachua the configuration was a single row planting. The treeless pastures were generally older than the silvopastures with the exception of the Suwannee location in which both pasture systems were of the same age (Table 3-2). Generally no fertilizers were applied to the pasture systems under study except for the treeless pasture in Suwannee, which received a 19-5-19 formulation respectively at a rate of 336 kg ha-1 and at 224 kg ha-1 during 2003 and 2004 respectively. The soils at both Alachua and Suwannee are Ultisols (Figure 3-5), whereas soils at Manatee and Osceola are Spodosols (Figure 3-6). The Spodosols are poorly drained soils as compared to Ultisols that are well drained. On average, the depth to the spodic horizon was 55 cm in the Spodosols (Table 3-1). Average annual precipitations range from 1233 to 1381 mm and the minimum water table depth at the Osceola and Manatee field sites were 25 and 15 cm, respectively. Slope percent vary from 0 to 8 percent at the study locations (Table 3-1).

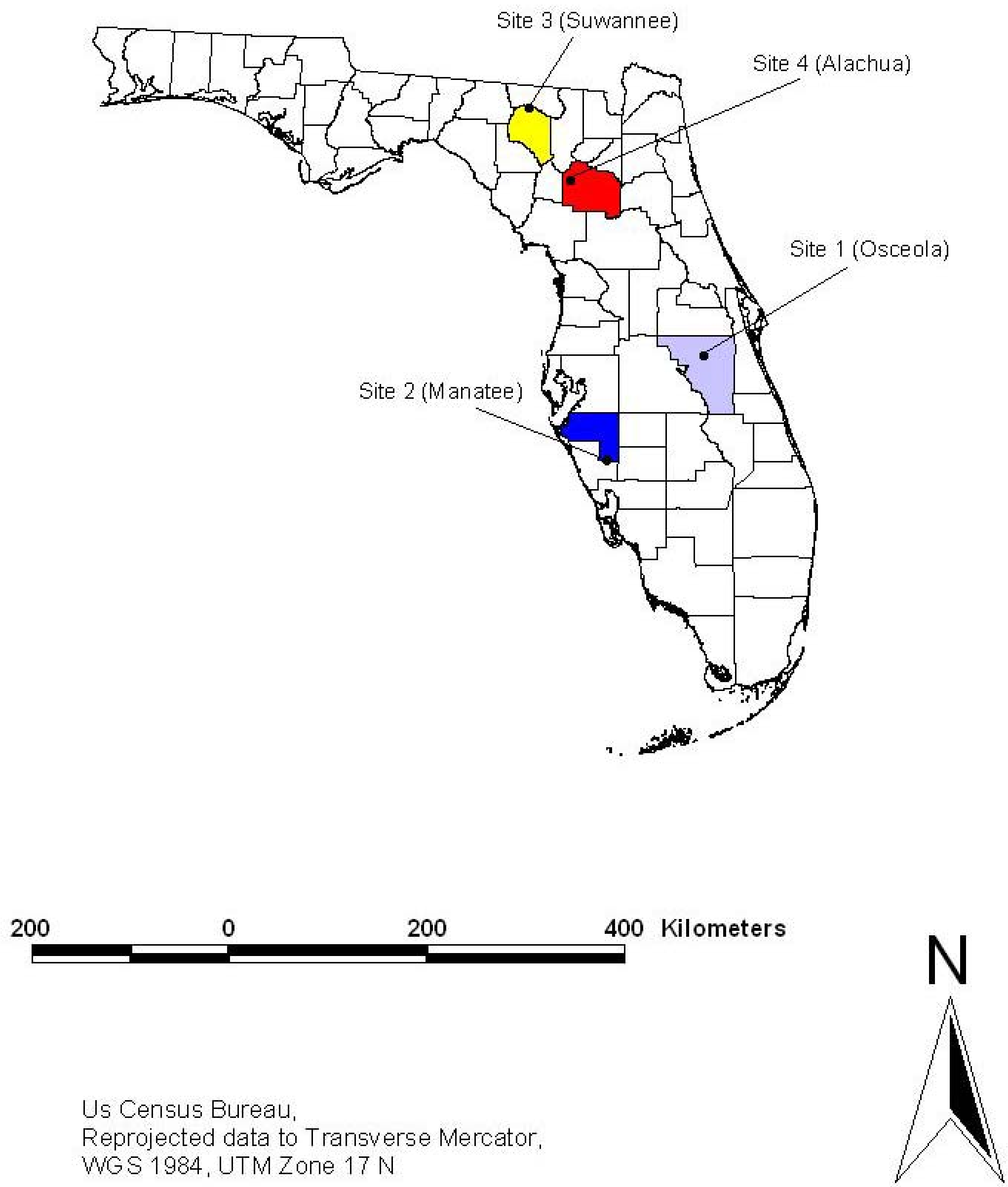

Figure 3-2. Location of study sites in Florida. The Osceola and Manatee sites are on Spodosols and the Alachua and Suwannee sites are on Ultisols.

Table 3-1. Soil and climatic characteristics of the four farms selected for the study in four counties of Florida

		Osceola County	Manatee County	Suwannee County	Alachua County
Location		28^{0} 9’ N, 81^{0} 10’ W Central Florida	27^{0} 13’ N, 82^{0} 8’ W Southwestern Florida	30^{0} 24’ N, 83^{0} 0’ W Florida Panhandle Region	29^{0} 45’ N, 82^{0} 33’ W North-central Florida
Soil	**Soil Series**	Immokalee: Sandy, siliceous, hyperthermic Arenic Alaquods	EauGallie: Sandy, siliceous, hyperthermic Alfic Alaquods	Blanton: Loamy, siliceous, semiactive, thermic Grossarenic Paleudults	Kendrick: Loamy, siliceous, semiactive, hyperthermic Arenic Paleudults
	Parent material	Thick marine deposits formed in thick beds of marine sands	Sandy and loamy marine sediments in Peninsula Florida	Sandy and loamy marine or eolian deposits	Thick beds of loamy marine sediments
	Slope (%)	0 – 2	0 – 2	0 – 8	0 – 8
	Annual fluctuation of the water table depth (cm)	25 – 102	15 – 45	–	–
	Drainage class	Poorly drained	Poorly or very poorly drained	Somewhat excessively to moderately well drained	Well drained; slow to moderately slow permeability
	Depth to spodic horizon (cm) (spodosols)	53	58		
Climate	**Avg. annual precipitation (mm)**	1233	1381	1366	1332
	Avg. annual air temperature (^{O}C)	22	22	20	21

Source: Soil survey of Osceola (Readle, 1979), Sarasota (Hyde et al., 1991); Alachua (Thomas et al., 1982); USDA-NRCS (not dated); World climate (2005); Florida Sheriffs Youth Ranch, 2003, unpublished; personal communication; and results of the study.

Table 3-2. Description of pasture systems at the four study locations in Florida

Pastoral Systems	Osceola	Manatee	Suwannee	Alachua
Silvopasture				
Tree species	Slash pine *Pinus elliotii*	Slash pine *Pinus elliotii*	Slash pine *Pinus elliotii*	Slash pine *Pinus elliotii*
Pasture species	Bahiagrass *Paspalum notatum*	Bahiagrass *Paspalum notatum*	Bahiagrass *Paspalum notatum*	Bahiagrass *Paspalum notatum*
Tree planting configuration (m)	Double rows 3.1 x 1.2 x 12.2	Double rows 3.1 x 1.2 x 12.2	Single rows 1.5 x 7.2	Single rows 1.5 x 3.0
Tree age (year)	12	12	40	8
Land area (ha)	8.5	20.2	16.2	28.3
Fertilization history	No fertilization	No fertilization	No fertilization	No fertilization
Prior land use history	Florida Flatwoods Treeless pasture for 15 years (Site continuously fertilized and limed when it was under treeless pasture system)	Florida Flatwoods	Agriculture	Grazed naturally occurring loblolly pine forest with grass
Treeless pasture				
Pasture species	Bahiagrass	Bahiagrass	Bahiagrass	Bahiagrass
Age (year)	45-50	30	40	55
Land area (ha)	6.1	3.0	16.2	7.3
Fertilization history	No fertilization	No fertilization	19-5-19 application at 336 kg ha^{-1} in 2003 19-5-19 application at 224 kg ha^{-1} in 2004 4.5 Mg ha^{-1} of dolomite applied every 4 years since 1978	No fertilization
Prior land use history	Florida Flatwoods	Florida Flatwoods	Agriculture	Agriculture (Corn field)

Figure 3-3. Silvopastoral system at Osceola County, Florida

Figure 3-4. Treeless pasture at Manatee County, Florida

Figure 3-5. Profile of an Ultisol. (Source: Collins, 2001)

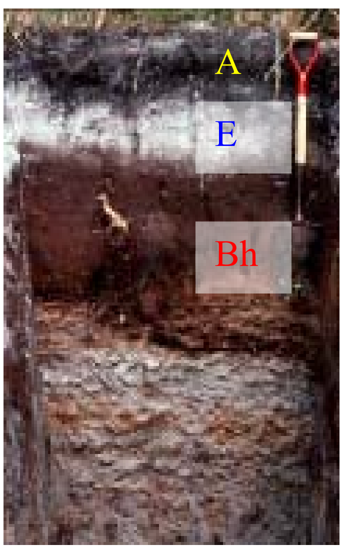

Figure 3-6. Profile of a Spodosol. (Source: Collins, 2001)

Estimation of Nitrogen and Phosphorus Loads in the Pasture Soils

An estimation of nitrogen and phosphorus loads in the pasture sites was made based on several assumptions (Table 3-3). According to Vicente-Chandler (1966), a mature cow produces 9.1 tons (1 Mg = 1 ton = 1000 kg) of excreta yearly containing a total of 71 kg N, 40 kg P_2O_5, and 59 kg K_2O. The total land grazed at the Manatee, Suwannee, Osceola and Alachua farms were 259, 567, 445, and 259 hectares respectively. Although grazing animals do not deposit urine and manure evenly across the paddocks where they grazed, an even distribution of cattle manure was assumed in this study (in the absence of a better way of presentation). Dalrymple (1994) reported from a rotational grazing study that urine spots occupied 16.7 percent of the pasture while manure spots occupied 18.8 percent, following 504 grazing days.

Table 3-3. Estimates of nutrient loads from beef cattle excreta at the four study sites

Location	Farm size (ha)	Head of Cattle	Load estimates (kg ha^{-1} yr^{-1})	
			N	P_2O_5
Alachua	259	150	41	23
Suwannee	567	200	25	14
Manatee	259	150	41	23
Osceola	445	275	44	25

Phosphorus and nitrate loads from beef cattle were similar in both Alachua and the Manatee sites (Table 3-3).The Suwannee sites had the lowest nutrient loads per unit area than all four sites which is the result of a lower cattle density. The highest nutrient loads per unit area were observed in the Osceola sites.

Major Tree and Grass Species at the Study Sites

***Pinus elliottii* (Slash pine).** Slash pine is an important timber species in the southeastern United States. Its strong, heavy wood is excellent for construction purposes.

Because of its high resin content, the wood is also used for railroad ties, poles, and piling (Duncan and Duncan, 1988; McCune 1988; Lohrey and Kossuth, 1990)

Slash pine is a large, stately, heavily-branched, long-needled conifer whose fast growth rate makes it capable of reaching 30.5 m in height and 0.9 to 1.2 m in diameter (Gilman and Watson, 1994). Slash pine is self-pruning of its lower branches, it forms a somewhat pyramidal canopy when young which evolves to an open, rounded canopy over time. Mature trees generate a light, draped shade beneath. Aggressive root competition takes place beneath pines, so the shrubs and lawn beneath and around the canopy often require more frequent irrigation, particularly during the dry season. Pines have some deep roots, except in poorly-drained soil where most roots proliferate near the soil surface. The tap root is prominent in well-drained soil and can make pines difficult to transplant in the wild. Slash pines grow well on a variety of acidic soils in either full sun or partial shade. It does poorly in high pH soil and so is not recommended for calcareous soils and where irrigation water has a high pH. Once established, it is more tolerant of wet sites than most other pine species, and is highly drought-tolerant (Lohrey and Kossuth, 1990)

***Paspalum notatum* (Bahiagrass).** Bahiagrass in an important forage species in Florida where it occupies more land area than any other single pasture species, covering an estimated 1 million hectare (Chambliss and Adjei, 2006). Most of this land area is used not only for grazing but also for the production of hay, sod, and seed harvested from pastures.

Bahiagrass is a warm-season perennial grown throughout Florida and in the Coastal Plain and Gulf Coast regions of the southern United States. It is a native to South

America and is widely distributed in Argentina, Uruguay, Paraguay and Brazil. Bahiagrass is adapted to climatic conditions throughout Florida and can be grown on upland well-drained sands as well as the moist, poorly-drained flatwoods soil of peninsular Florida (Chambliss and Adjei, 2006); LSU, 1998). Bahiagrass is popular with Florida ranchers because it tolerates a wider range of soil conditions than other improved grasses, has the ability to produce moderate yields in soils of very low fertility, is easily established from seed, withstands close grazing, and is relatively free from damaging insects (except for mole crickets) and diseases.

Soils of the Study Sites

Soil sampling

Soil samples were collected during summer and fall 2004 at the four locations (Figures 3-7 to 3-10) at the following sampling depths: 0 – 5, 5 – 15, 15 – 30, 30 – 50, and 50 – 75 and 75 – 100 cm using a bucket soil auger (21 cm x 7 cm). A grid sampling procedure was used (Figure 3-7). With eight plots, each with 24 sampling points and six depths, there were a total of 1152 soil samples. Soil samples were taken in the alleys in the silvopastoral systems. The spacing between the sampling points in both the regular pasture and the silvopasture plots was based on the size of the plots. Soil Survey (hard copies) and Soil Survey digital maps [Natural Resources Conservation Service (NRCS), Soil Service Geographic (SSURGO)] of the area to be sampled were used to obtain information on the soil series. A hand-held GPS unit (eTrex^{TM}, GARMIN$_{®}$, personal navigator) was used to obtain the geographic coordinates of each the sampling point.

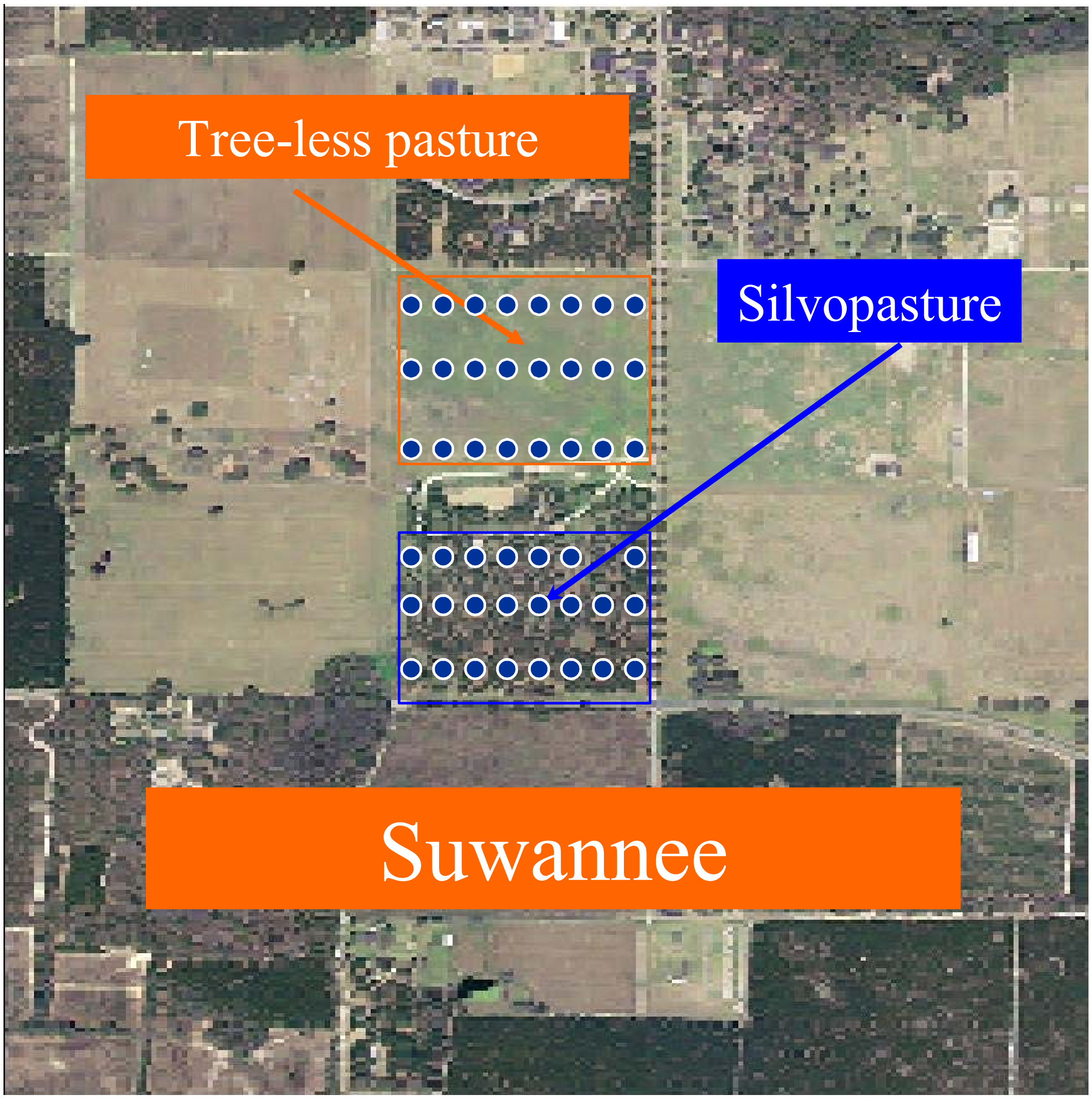

Figure 3-7. Grid sampling at the Suwannee location. Twenty four soil profiles were collected at each field (silvopasture and treeless pasture) at each location, and with 6 depths (0 – 5, 5 – 15, 15 – 30, 30 – 50, and 50 – 75 and 75 –100 cm) per profile. The small circles, representing sampling points, illustrate the layout of the grid sampling method used in each sites at each location.

Soil-nutrient characterization

Mehlich-1 (0.0125*M* H_2SO_4 and 0.05*M* HCl)-extractable Fe, Al, Ca, and Mg were obtained using a 1:4 soil to double acid ratio (Mehlich, 1953). The metals in the Mehlich-1 solutions were determined by atomic absorption spectrometry.

Soil texture and pH determination

Soil texture was determined by the hydrometer method following the analytic procedure describe by Arshad et al. (1996). Soil pH (2:1) was assessed using the analytical procedure described by Smith and Doran (1996).

Statistical Procedures

The statistical analyses were performed using SAS (PROC ANOVA) 8.2 for Windows. The experimental design used was a 4-fold nested model (Table 3-4). The statistical model used was the following:

$$Y_{ijk} = \mu + \alpha_i + \beta_{ij} + \gamma_{ijk} + \delta_{ijkl}$$

where

μ = grand mean

α_i = effect of level *i* of location (Alachua, Suwannee, Osceola and Manatee)

β_{ij} = effect of level *j* of treatment (Silvopasture and treeless pasture), nested within level *i* of location

γ_{ijk} = effect of level *k* of plot (24 sampling points), nested within level *j* of treatment which is nested within level *i* of location

δ_{ijkl} = effect of level *k* of depth (6 depths), nested within level k of plot which is nested in level *j* of treatment which is nested in level *i* of location

Table 3-4. Statistical model used in the study[Q]

Source	Degree of Freedom
Location	3
Treatment (location)	4
Plot (Treatment x location)	184
Depth (Treatment x location x plot)	960
Total	1151

[Q]The hypotheses were tested using the ANOVA mean square for treatment (location) as the error term for location, the ANOVA mean square for plot (treatment x location) as the error term for treatment (location), and the ANOVA mean square for depth (treatment x location x plot) for plot (treatment x location).

Results and Discussion

Soil Reaction (pH)

Soil pH for the 0 – 5 cm depth for the silvopasture and treeless pasture in Alachua were 5.4 and 5.2 respectively. The corresponding values for the Suwannee, Manatee, and Osceola field sites were 4.7 and 6.6; 4.8 and 4.4; 4.5 and 4.4 (Tables 3-5 to 3-8). The soil pH was different between the two pasture systems for all soil layers at the Suwannee location with the treeless pasture having the highest pH. Results from the Suwannee location can be explained by the fact that the treeless pasture site has been continuously limed at the rate of 4.5 Mg ha^{-1} every 4 years since 1978. In Alachua, soil pH was only found different at surface horizon with the treeless pasture site having lower pH values. This is not consistent with the general perception that conifer (e.g., pines and firs) stand tend to acidify the soil. Soil acidification is enhanced by most coniferous vegetation because of the acidic nature of their resinous needles which tend to accumulate in a thick O horizon (Brady and Weil, 2002). The difference in soil pH observed in Alachua maybe attributed to some variation in the parent material across the farm (e.g. limestone deposits).

At the Manatee site soil pH was similar for both systems across all soil depths. In Osceola differences in soil pH were only observed below 30 cm of depth with the treeless pasture having the higher pH values. It is important to remember that soil samples were only taken in the alleys in the silvopastures; therefore there could be differences in pH near the pine trees. In general the soil pH in the two pasture systems at in all four locations were in the desirable ranges for bahiagrass (<5.5 – 6.4) (Sartain, 2001) throughout the soil profile of the sites.

Soil pH of in the similar range as been reported by Nair and Graetz (2002) for the A, E, Bh, and Bw soil horizons of a beef pasture site (Spodosols) situated in the Okeechobee County of Florida.

Soil Particle Size Analysis (Soil Texture)

The soils at Alachua, Suwannee, Osceola ,and Manatee were designated as Kendrick (Loamy, siliceous, semiactive, hyperthermic Arenic Paleudults), Blanton (Loamy, siliceous, semiactive, thermic Grossarenic Paleudults), Immokalee (Sandy, siliceous, hyperthermic Arenic Alaquods), and EauGallie (Sandy, siliceous, hyperthermic Alfic Alaquods) soil series, respectively (Table 3.1). For the Alachua field site, the percent sand, silt, and clay for the 0 – 5 cm depth were 87, 4, and 9 and 92, 3, and 5% for the treeless pasture and silvopasture, respectively. The corresponding values for Suwannee were 94, 2, and 4% vs. 95, 3, and 3% compared to 94, 3, and 3% vs 95, 3, and 2% (Manatee), and 92, 4, and 4% vs. 96, 2, and 2% in Osceola (Table 3-5 to 3-8). In general, sand, silt and clay content was similar for both production systems across all soil depths. In Suwannee the treeless pasture had a higher clay content in the upper soil layer. The lack of differences in the soil texture between the two pastures at the four locations sites is desirable since it facilitates the comparison of the two land use systems in terms of there nutrient status. The clay content of the Ultisols at 75 – 100 cm depths was higher compared to the Spodosols, which is consistent with the known characteristics of these two soil orders (Collins, 2003).

Mehlich-1 Al and Fe Concentrations

Mehlich-1 Al concentrations at 0–5 cm depth for the silvopasture and treeless pasture in Alachua were 436 and 479 mg kg^{-1} respectively. The corresponding values were 160 and 183 mg kg^{-1} (Suwannee), 48 and 36 mg kg^{-1} (Manatee) compared to 225 and 132 mg kg^{-1}in Osceola (Tables 3-5 to 3-8). Concentrations of Mehlich-1 extractable Fe at the top 0 – 5 cm depth in the silvopasture and treeless pasture in Alachua were 28 and 43 mg kg^{-1}, respectively. The corresponding values were 25 and 10 mg kg^{-1} (Suwannee), 18 and 18 mg kg^{-1} (Manatee), while values at Osceola were 13 to 27 mg kg^{-1} (Tables 3-5 to 3-8). In Alachua, Mehlich-1 Al concentrations among the production systems were different below 15 cm of depth. In contrast, Mehlich1-Fe concentrations were different between the two pasture systems (Alachua) throughout the soil profile from the top 0 – 5 cm to 75 – 100 cm depth. Differences in Al concentrations between the two pasture sites within a location may be attributed to variation in clay content. The higher the clay content of a soil the higher its Al concentration will be.

In Suwannee, there were generally no differences in Mehlich-1 Al and Fe concentration among land use systems through out the entire soil profile. With the exception of 0 – 5 and 75 – 100 depths, both Mehlich-1 Al and Fe concentrations were not different between the pasture systems in Manatee. The level of these elements in the soil was very low at the surface horizons in Manatee, which is a characteristic of Spodosols. The Mehlich-1 Al content of the two pasture sites in Osceola showed no difference throughout the soil profile. Iron concentration in the soil of the two pasture systems was found to be different only at 5 – 15, 50 – 75, and 75 – 100 cm depths.

A strong relationship between Mehlich-1 Fe, and diagnostic tissue levels of Fe, concentrations and a predictable responses to applied Fe has not being found, therefore the University of Florida Extension Soil does not make fertilization requirement based on extractable Fe (Sartain, 2001).

Average values for Mehlich-1 Al and Fe concentrations for the Ultisols and the Spodosols were 315 and 110 mg kg^{-1} and 27 and 19 mg kg^{-1}, respectively, at depth 0 – 5 cm respectively. Results of the study showed that Ultisols generally had greater Mehlich-1 Al concentration then Spodosols in the surface soil horizons (from 0 – 5 cm to 15 – 30 cm depth) [Table 3-9]. Below the 30 cm soil depth no significant difference in Al was observed between the soil types. Ultisols had the highest Fe concentration at 15 – 30 and 75 – 100 cm. The higher Al concentrations observed in the Ultisols at the surface horizons is an indication of the greater P retention capacity of this soils in the surface horizons as compared to Spodosols since the amount of aluminum and iron oxides and hydroxides in acid soils is a determinant factor in the amount of P that can be held by a soil. At the deeper soil horizons no differences were observed between the two soil types because the spodic horizon may have comparable levels of Al and Fe. These results are consistent with Mansell et al. (1991) observations that the A and E horizons of Spodosols are sandy and have poor sorption capacities while the spodic horizon have much greater affinities for P retention. Nair and Graetz (2002) found Mehlich-1 Al and Fe concentrations of 38.1, 9.0, 385 and 635 and 13.2, 7.52, 46.1, and 32.8, respectively, for the A, E, Bh, and Bw soil horizons of a beef pasture site (Spodosols) of the Okeechobee County of Florida.

Mehlich-1 Mg and Ca Concentrations

Mehlich-1 Mg concentrations for the silvopasture and treeless pasture in Alachua for the 0 – 5 cm depth were 132 and 223 mg kg^{-1}, respectively. The corresponding values were 72 and 154 mg kg^{-1} (Suwannee), 132 and 154 mg kg^{-1} (Manatee), compared to 100 and 70 mg kg^{-1}in Osceola (Tables 3-5 to 3-8). In Alachua concentrations of Mehlich-1 extractable Ca in the top 0 – 5 cm depth for the silvopasture and the treeless pasture were 727 and 1006 mg kg^{-1}, respectively. Values in Suwannee were 531 and 921 mg kg^{-1} compared to 1029 and 911 mg kg^{-1} in Manatee, while values in Osceola were 663 to 596 mg kg^{-1} (Tables 3-5 to 3-8). Similar Mehlich-1 Ca and Mg concentrations for the A, E, Bh, and Bw soil horizons of a beef pasture site (Spodosols) in Okeechobee County (S-Florida) of Florida were reported by Nair and Graetz (2002). Mehlich-1 Mg and Ca concentrations were found to be different among the pasture systems in both Alachua and Suwannee with the highest concentration found in the treeless pasture. Based on UF/IFAS diagnostic soil test interpretations (Kidder et al., 2002) Mg concentration were generally in the high range (>30 mg kg^{-1}) in both the treeless pasture and the silvopasture sites throughout the soil profile in Alachua. Soil Mg concentration was in the high range in the treeless pasture throughout the soil profile and in the low range (<15 mg kg^{-1}) in the silvopasture below 5 cm of depth in Suwannee base on UF/IFAS interpretation system.

In general, Mehlich-1 Mg and Ca concentrations were similar for both production systems in Manatee. The Mg concentration in two pasture sites was found to be in the low range according to UF/IFAS interpretations. In Osceola Mehlich-1 Ca concentration were also similar throughout sampled soil profile (up to 100 cm, which was the deepest position studied), whereas Mehlich-1 Mg concentration was generally different. Soil Mg concentration in the two pasture systems in Osceola was in the low range below 30 cm of depth. In Manatee, the silvopasture and the treeless pasture sites had Mg concentration in the high range at the surface 0 – 5 cm depth, whereas Mg concentration below 30 cm of depth where in the low range.

No interpretation is made for Mehlich-1 extractable Ca levels because the extraction method dissolves soil calcium compounds which are not readily available for the plants. Generally, Ca levels tend to be adequate for turfgrass growth in Florida soils due the fact that they are inherently high in Ca, have a history of Ca fertilization, or receive Ca regularly through irrigation with high Ca water (Kidder et al., 2002).

Conclusions

The soils at the study sites typically had a rather coarse (sandy) texture, especially in the upper layers, and in the absence of liming may be prone to acidification and are typical of the southeastern USA. Soil pH at the study sites were in the recommended range for bahiagrass. In general the treeless pastures had higher pH values compared to the silvopastures. Magnesium concentration levels in the treeless pasture sites were generally higher than the silvopasture sites. Soil test values for agronomic crops were “high” in Mg in the upper 0 – 5 cm at all four locations. Calcium concentration levels were generally not different in the two pasture systems in Osceola and Manatee. Except in Alachua where the treeless pasture had the highest Al levels of the two pasture systems, no differences in Al concentrations were generally observed between the two pastures. Iron concentrations were in general higher in the silvopasture as compared to the treeless pasture in Alachua and Suwannee but this trend was not significant in Osceola and Manatee. Soil Fe concentration level was found to be of lower magnitude at all the four locations. The Ultisols had higher soil Al and Fe concentrations than the

Spodosols in the upper 30 cm of the soil profile. Higher clay content was also observed in the deeper 75 – 100 cm depth in the Ultisols. The information presented here is critical to the explanation of the results presented in the subsequent chapters.

Table 3-5. Mean values of Mehlich-1 Ca, Al, Mg, and Fe concentrations, pH, and percent sand, silt and clay for soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Alachua Florida, USA.

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	*P*
Depth (cm)	Ca (mg kg^{-1})		*P*	Al (mg kg^{-1})		*P*	Mg (mg kg^{-1})		
0-5	727	1006*	0.0067	436	479	0.3970	132	223*	0.0001
5-15	359	920*	0.0001	499	563	0.1338	48	126*	0.0001
15-30	215	946*	0.0001	429	531*	0.0204	32	151*	0.0001
30-50	169	969*	0.0001	359	608*	0.0004	32	216*	0.0001
50-75	132	999*	0.0001	285	660*	0.0001	39	252*	0.0001
75-100	182	1147*	0.0001	272	744*	0.0001	52	239*	0.0001

	Silvopasture	Treeless pasture	*P*	Silvopasture	Treeless pasture	*P*	Silvopasture	Treeless pasture	*P*
Depth (cm)	Fe (mg kg^{-1})			pH (1:2)			Sand (%)		
0-5	28	43*	0.0005	5.4	5.2*	0.0184	92	87	0.4952
5-15	27	43*	0.0001	5.6	5.4*	0.0061	91	86	0.4225
15-30	25	44*	0.0001	5.8	5.8	0.7324	92	80	0.3792
30-50	25	45*	0.0001	5.8	5.8	0.3964	91	76	0.4173
50-75	22	38*	0.0001	5.6	5.7	0.0985	92	78	0.3891
75-100	18	37*	0.0001	5.4	5.6	0.0632	89	79	0.5366

	Silvopasture	Treeless pasture	*P*	Silvopasture	Treeless pasture	
Depth (cm)	Silt (%)			Clay (%)		
0-5	3	4	0.6851	5	9	0.4415
5-15	4	5	0.4540	5	8	0.4355
15-30	7	7	0.9931	1	13	0.2511
30-50	4	7	0.4337	4	16	0.3948
50-75	4	7	0.3258	5	15	0.4091
75-100	4	7	0.4047	8	15	0.5800

[(*Indicates significant P values within a given depth (p<0.05)]

Table 3-6. Mean values of Mehlich-1 Ca, Al, Mg, and Fe concentrations, pH, and percent sand, silt and clay for soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Osceola Florida, USA.

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Ca (mg kg^{-1})		*P*	Al (mg kg^{-1})		*P*	Mg (mg kg^{-1})		*P*
0-5	663*	596	0.0425	225	132	0.2300	100*	70	0.0425
5-15	470	529	0.6351	181	156	0.7845	24*	14	0.0346
15-30	454	336	0.0487	181	235	0.6060	21*	5	0.0021
30-50	257	246	0.8618	298	786	0.0810	9*	4	0.0003
50-75	166	204	0.4078	395	428	0.7419	9*	4	0.0001
75-100	110	169	0.1296	428	364	0.4600	8*	4	0.0004

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Fe (mg kg^{-1})		*P*	pH (1:2)		*P*	Sand (%)		*P*
0-5	13	27	0.0903	4.5a	4.4a	0.1257	97	92	0.0542
5-15	9	30*	0.0001	4.6a	4.5a	0.7654	98	92	0.1818
15-30	11	12	0.8071	4.7a	4.9a	0.1221	98	92	0.1383
30-50	5	11	0.0541	4.6a	4.9b	0.0456	95	94	0.5401
50-75	4	8*	0.0320	4.5a	4.8b	0.0175	96	96	0.7798
75-100	3	6*	0.0393	4.4a	4.7b	0.0484	97	95	0.4774

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Silt (%)		*P*	Clay (%)		*P*
0-5	2	4	0.1277	1	4*	0.0143
5-15	1	6	0.1099	1	2	0.3932
15-30	2	5	0.1807	1	3	0.0761
30-50	3	4	0.6209	1	3	0.5017
50-75	2	2	0.6690	2	2	1.0000
75-100	2	3	0.5562	2	2	0.3746

[(*Indicates significant P values within a given depth (p<0.05)]

Table 3-7. Mean values of Mehlich-1 Ca, Al, Mg, and Fe concentrations, pH, and percent sand, silt and clay for soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Suwannee Florida, USA.

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Ca (mg kg^{-1})		*P*	Al (mg kg^{-1})		*P*	Mg (mg kg^{-1})		*P*
0-5	531	921*	0.0119	160	183	0.2232	72	154*	0.0001
5-15	78	689*	0.0001	253	266	0.6034	9	55*	0.0001
15-30	40	316*	0.0001	246	259	0.6260	6	28*	0.0001
30-50	36	232*	0.0001	184	230	0.0078	6	22*	0.0001
50-75	30	166*	0.0001	141	190*	0.0423	5	15*	0.0001
75-100	27	132*	0.0001	123	151	0.1581	6	15*	0.0041

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Fe (mg kg^{-1})		*P*	pH (1:2)		*P*	Sand (%)		*P*
0-5	25*	10	0.0001	4.7	6.6*	0.0001	95	94	0.0700
5-15	28*	16	0.0001	4.9	6.1*	0.0001	95	94	0.4226
15-30	19*	14	0.0052	5.1	6.0*	0.0001	94	94	0.2999
30-50	16*	12	0.0063	5.1	6.0*	0.0001	94	94	0.6020
50-75	14*	10	0.0043	5.1	6.1*	0.0001	94	95	0.7758
75-100	13	10	0.0709	5.0	6.1*	0.0001	84	94	0.4641

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Silt (%)		*P*	Clay (%)		*P*
0-5	3	2	0.2513	3	4*	0.0133
5-15	3	3	0.6906	2	2	0.1573
15-30	3	4	0.6414	2	3	0.3268
30-50	4*	3	0.3217	2	3	0.1919
50-75	4	3	0.3057	2	3	0.1548
75-100	8	3	0.3804	8	3	0.5324

[(*Indicates significant P values within a given depth (p<0.05)]

Table 3-8. Mean values of Mehlich-1 Ca, Al, Mg, and Fe concentrations, pH, and percent sand, silt and clay for soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Manatee Florida, USA.

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Ca (mg kg^{-1})		*P*	Al (mg kg^{-1})		*P*	Mg (mg kg^{-1})		*P*
0-5	1029	911	0.2076	48*	36	0.0060	132	154	0.1977
5-15	446	422	0.6161	19	17	0.3668	18	26*	0.0489
15-30	175	132	0.0641	14	8	0.1048	4	5	0.2427
30-50	101	74	0.1158	56	15	0.2783	6	3	0.3196
50-75	181	157	0.2997	144	121	0.4130	5	4	0.4792
75-100	135	200*	0.0029	246*	129	0.0002	8	8	0.5845

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	*P*
Depth (cm)	Fe (mg kg^{-1})		*P*	pH (1:2)		*P*	Sand (%)		
0-5	18	18	0.8605	4.8*	4.4	0.0001	95	94	0.5124
5-15	16	14	0.2445	4.9	4.8	0.1748	98	89	0.3991
15-30	11*	6	0.0001	5.3	5.1	0.1731	98	98	0.2929
30-50	9	10	0.8165	5.4	5.3	0.0952	98	98	1.0000
50-75	62	55	0.7010	5.6	5.7	0.1956	97	97	0.1296
75-100	77	90	0.4873	5.5	5.8*	0.0030	97	97	1.0000

	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	Silt (%)		*P*	Clay (%)		*P*
0-5	3	3	0.7758	2	3	0.4073
5-15	2	10	0.3950	1	1	0.4453
15-30	1	1	0.4929	1	1	0.2137
30-50	2	1	0.7758	0	1	0.7202
50-75	2	2	0.5425	0.8	1.2*	0.0299
75-100	2	2	0.0513	1.5	1.2	0.0955

[(*Indicates significant P values within a given depth (p<0.05)]

Table 3-9. Mean values of Mehlich-1 Al and Fe concentrations and percent sand, silt and clay for soil profiles of the Ultisols and the Spodosols.

	Ultisols	Spodosols		Ultisols	Spodosols	
Depth	Al		*P*	Fe		*P*
(cm)	--------(mg kg^{-1})-----			--------(mg kg^{-1})------		
0-5	315*	110	0.0224	27	19	0.1702
5-15	395*	93	0.0045	29	17	0.1368
15-30	366*	110	0.0143	26*	10	0.0416
30-50	345	289	0.7147	24	9	0.0749
50-75	319	272	0.7011	32	21	0.0803
75-100	323	292	0.8370	44*	20	0.0479

	Ultisols	Spodosols	*P*	Ultisols	Spodosols	*P*
Depth (cm)	-------------Sand (%)------------			------------Silt (%)-------------		
0-5	92	95	0.3242	3	3	0.7351
5-15	92	94	0.5508	4	5	0.8862
15-30	90	96	0.1980	5	2	0.0951
30-50	89	96	0.1752	5*	2	0.0428
50-75	90	97	0.1597	4	2	0.0601
75-100	86	96*	0.0018	5*	2	0.0286

	Ultisols	Spodosols	*P*
Depth (cm)	----------Clay (%)-----------		
0-5	5	3	0.2636
5-15	3	1	0.1023
15-30	5	1	0.3856
30-50	6	1	0.2633
50-75	6	1	0.2142
75-100	9*	2	0.0048

[*Indicates significant P values (p<0.05)]

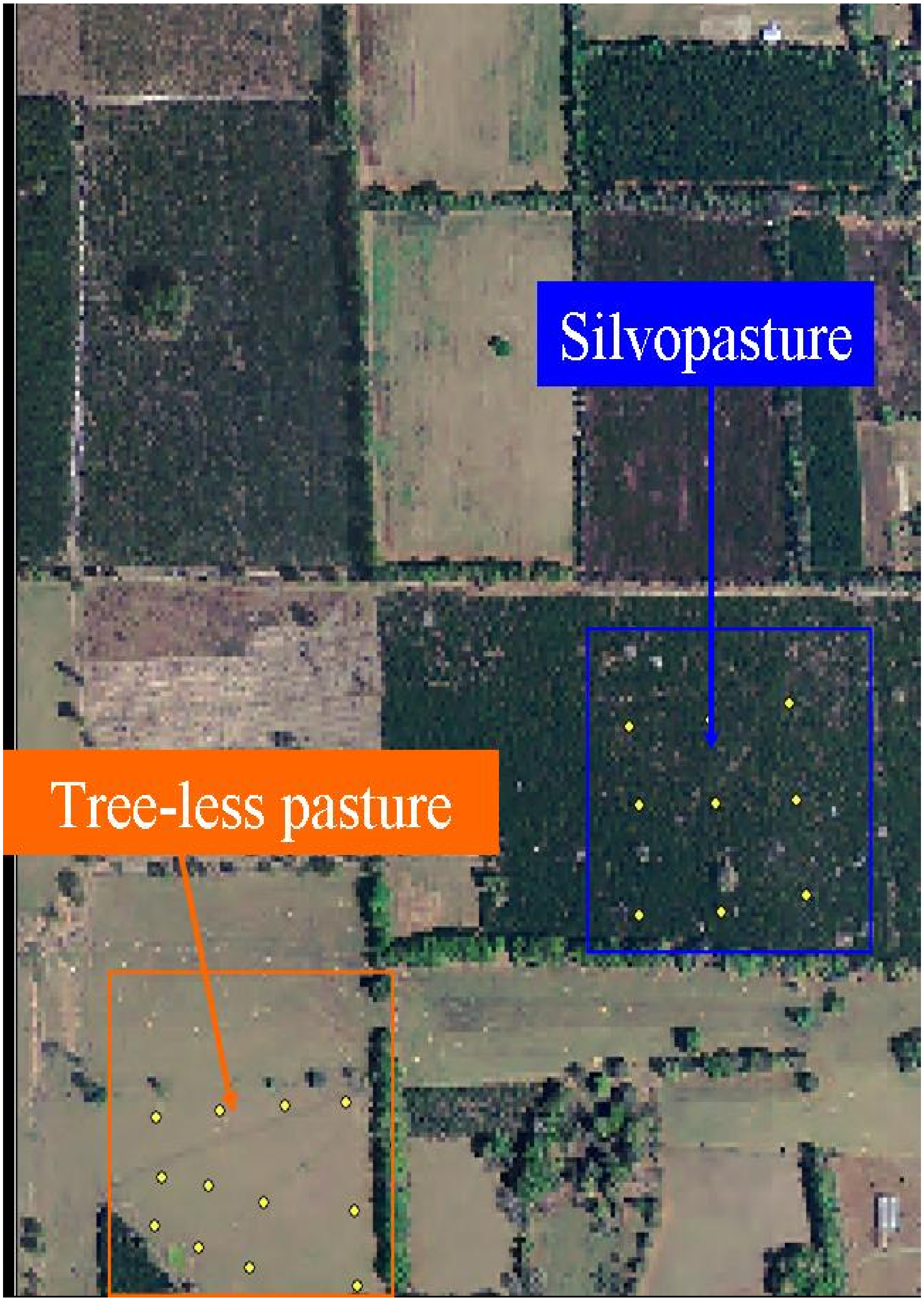

Figure 3-8. Aerial photo of the Alachua location

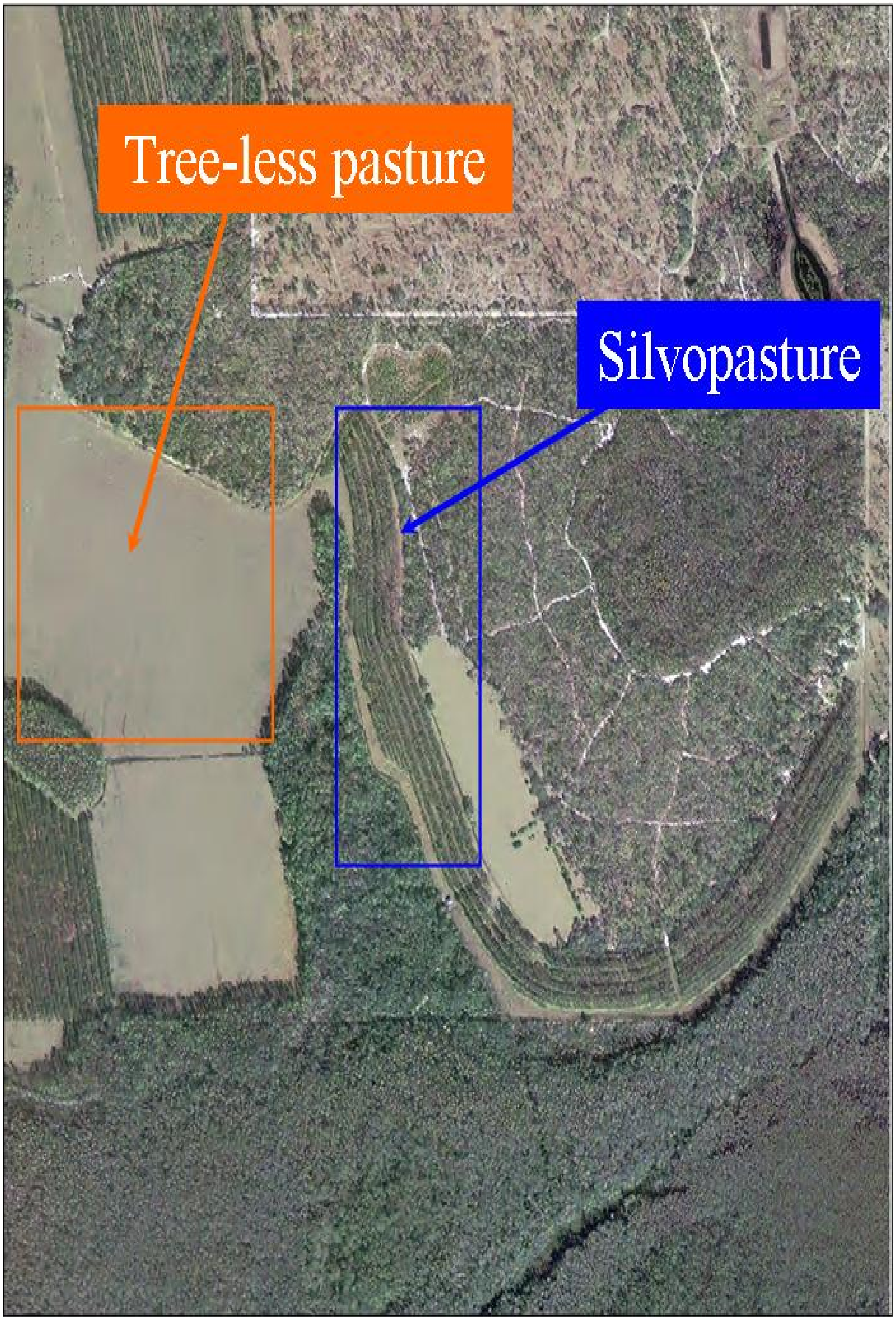

Figure 3-9. Aerial photo of the Osceola location

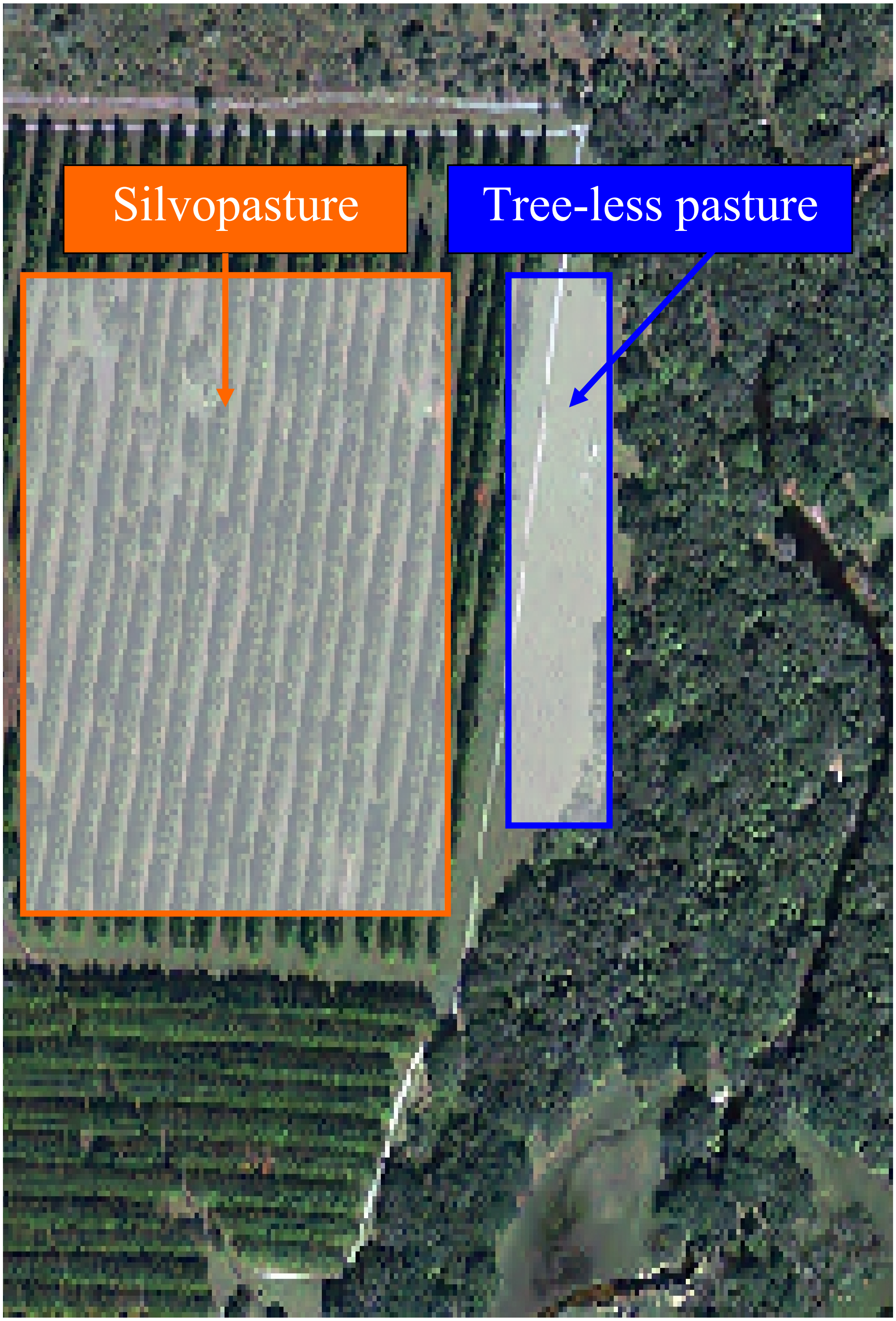

Figure 3-10. Aerial photo of the Manatee location

CHAPTER 4
PHOSPHORUS AND NITROGEN CONCENTRATIONS UNDER A SLASH PINE (*Pinus elliottii*) + BAHIAGRASS (*Paspalum notatum*) SILVOPASTURE AND A TREELESS PASTURE

Introduction

Non-point pollution is a major source of phosphorus (P) and Nitrate-N to surface waters of the United States (Carpenter et al., 1998). Phosphorus concentrations in excess of 0.02 mg L^{-1} in lake water can lead to accelerated eutrophication (Sharpley et al., 1999). Nitrate-N concentration in excess of 10 mg L^{-1} in drinking water may lead to the "blue baby syndrome"(USEPA, 2006). Soil receiving large quantities of livestock manure can accumulate significant amounts of P and result in excessive P loss to surface and ground water through surface runoff and subsurface leaching.

Studies in tropical agroforestry systems on nutrient-poor soils have shown that deep roots of trees in agroforestry systems can absorb nutrients that have leached below the rooting zone of associated agronomic crops, and subsequent deposition of litter and root materials facilitate enhanced nutrient recycling and thereby improve the nutrient-use efficiency in the system as a whole (Young, 1997). Furthermore, tree roots tend to be long-lived and even in the upper soil layers they enhance nitrate and phosphorus retention before and after the crop is planted and harvested (Jose et al., 2004). In essence, this would enhance the overall resource-use efficiency of the system (van Noordwijk et al., 2004). Although, the vertical distribution of a given species' root system in its natural niche may follow a distinct pattern, leading to overlapping root distributions, some species are able to respond to changes in nutrient supplies or restricting soil layers) (Jose et al., 2004). This has been demonstrated by Wanvestraut et al. (2004) in a study conducted in pecan (*Carya illinoensis*) + cotton (*Gossypium hirsutum*) alley cropping system in northwestern Florida. They observed that cotton roots exhibited a degree of plasticity, being limited by shallow soil strata and they also avoided a region of high pecan root density deeper in the soil. In another study conducted at the same site, Allen et al. (2003) reported a 34% reduction in nitrate nitrogen concentration in the soil solution at 0.9 m depth when pecan and cotton roots were not separated by a root barrier compared to the "root-barrier" treatment, suggesting the potential safety net role of pecan roots. This safety net hypothesis can also be used to explain the sediment and nutrient capture functions of riparian buffer strips. Riparian buffers have been presented as a tool for removing non-point source pollutants from farmlands (Addy et al., 1999; Bharati et al., 2002; Lee et al., 2003; Schultz et al. 2004). In a study conducted by Lee et al. (2003) in central Iowa, Midwestern United States, a switch grass (*Panicum virgatum*)/woody buffer treatment removed 90% of the sediment, 85% nitrate-N, and 80% of the P in the runoff. The integration of the woody component in the buffer strip increased the uptake efficiency of soluble nutrients by over 20%. Other applications of the safety-net include phytoremediation of contaminated sites (Rockwood et al., 2004) and rehabilitation of heavily fertilized agricultural soils in Florida soils (Nair and Graetz, 2004). Thus, while the 'safety-net' concept is critical for enhancing nutrient use efficiency and improving crop production under tropical conditions, it has a different application in the heavily fertilized and excessively drained soils of Florida that have limited nutrient retention capacity. The tree roots' ability to retrieve nutrients from deeper soil layers can be exploited advantageously to increase the apparent nutrient retention in excessively drained soils and thereby reduce the amount of nutrients that might otherwise be transported to surface water through runoff and leaching and thereby cause non-point-source pollution of these water bodies.

Water soluble P (WSP) , a environmental soil testing method for environmental assessment of available soil P, can better represent the rapid release of P to water than stronger chemical extractant (such as agronomic soil P tests), since rainfall has similar properties than distilled water (Moore et al., 1998). This extractant is also known to maintain the soil pH within one unit of its original value, an important characteristic since P solubility is strongly dependent on soil pH (Golterman, 1998; Sharpley, 1993). Furthermore, a strong positive correlation exists between water soluble P and P in runoff (Pote et al., 1996).

The objective of this study was to quantify water soluble P (WSP), Mehlich-1 P, and nitrate and ammonium concentrations in surface and subsurface horizons in soil profiles of silvopastoral and treeless pasture systems at four different locations of two soil orders in Florida.

Materials and Methods

Site Description

The research was conducted on four slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) silvopastoral systems located in Osceola (28^0 9' N, 81^0 10' W), Manatee (27^0 13' N, 82^0 8' W), Suwannee (30^0 24' N, 83^0 0' W), and Alachua (29^0 45' N, 82^0 33' W) counties in Florida. A grid sampling procedure was adopted to collect 24 soil profiles from each location during summer and fall 2004. The soil samples were collected by depth: 0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75 and 75 – 100 cm. The soils in both

Manatee and Osceola counties are Spodosols, whereas those in Alachua and Suwannee are Ultisols. Refer to Chapter 3 for more in-depth details of the site description.

Statistical Procedures

The statistical analyses were performed using SAS PROC ANOVA (SAS 8.2 for Windows). The experimental design used was a 4-fold nested model (see Chapter 3 for the description of the model).

Water Soluble P and Mehlich-1 P Determination

Water soluble P was determined by extracting the soil with distilled dionized water using a 1:10 soil to water ratio. This mix was shaked with a mechanical shaker for 1 hour and filtered through a 0.45-μm filter using vacuum filtration. Mehlich 1 (0.0125*M* H_2SO_4 and 0.05*M* HCl)-extractable P was obtained using a 1:4 soil to double acid ratio (Mehlich, 1953). Phosphorus in solution was determined by an autoanalyzer (USEPA, 1993; Method 365.1) by the Murphy-Riley (1962) method.

Nitrate and Ammonium-N Determination

Nitrate and ammonium-N extracts were obtained using a 1:10 soil to KCL (2*M*) ratio. This mix was shaked on a mechanical shaker for 1 hour. The KCl suspension was then filtered by vacuum filtration as described above. A membrane filter of 0.45μm was used for the extraction. After extraction ammonium-N in the KCl extractant was determined using a semi-automated colorimetric analysis (USEPA Method 350.1, USEPA, 1993). Nitrate was determined using a semi-automated colorimetric analysis (USEPA Method 353.2, USEPA, 1993). Only 6 out of the 24 soil profiles taken in each sites were analyzed for nitrate and ammonium content. With eight sites, each with 6 sampling points and six depths, a total of 288 soil samples were analyzed.

Results and Discussion

Water Soluble P Concentrations

WSP concentrations at the 0 – 5 cm depth in the silvopasture and treeless pasture on Alachua were 5.6 and 10.9 mg kg^{-1}, respectively. Corresponding values in Suwannee were 4.1 and 10.1 mg kg^{-1} compared to 11.4 and 23.4 mg kg^{-1} in Manatee, and values of 1.4 and 11.0 mg kg^{-1}in Osceola (Tables 4-1 and 4-2 and Figures 4-1 and 4-2). Differences in WSP concentrations were found through out the soil profile (up to 100 cm) between the two pasture systems in Alachua, Manatee and Suwannee. In Osceola, WSP concentrations was found to be different between the two pasture systems at 0 – 5, 15 – 30, 30 – 50, and 75 – 100 depths. Water soluble P was generally higher in the treeless pastures throughout the soil profile, indicating the safety net role of slash pine roots. Nair and Graetz (2004) found that water soluble P concentrations in the surface soils of a Spodosols varied throughout the soil profile in the order of pasture > silvopasture > native flatwoods vegetation. They reported WSP concentrations of 9.1, 4.2, and 1.6 mg kg^{-1} in the top 0 – 5 cm depth, respectively, in a treeless pasture, silvopasture, and native flatwoods. Even in an Ultisol with substantial P retaining clay below 20 cm, there appears to be movement of P to lower depths. Below the retentive clay layer the treeless pasture contained more P in the soil than the silvopasture (Figure 4-2) suggesting removal of P from the lower depths by the trees in the silvopasture systems. This observation suggests that the likelihood of P moving out of the soil is greater under a treeless pasture than under a tree-based system. These findings are consistent with that of a study conducted by Friend et al. (2006) on a loblolly pine (*Pinus taeda*) stand. In this study dry poultry-litter applications of approximately 5 Mg ha^{-1} to mid-rotation loblolly pine stands would be contained by the ecosystem and may result in significant increases in tree growth.

Although we would expect to find higher WSP concentrations in the Spodosols, which have lower P retention capacity, especially in the surface A and E horizons as opposed to the Ultisols, the results do not support this expectation (Table 4-2). These findings could be explained by the hydrological dynamics of the Spodosols that have seasonally and highly fluctuating water table. Spodosols are characterized by a highly fluctuating water table situated between the Bh (a layer form by the accumulation of organic matter and/or iron and aluminum oxides) and the A horizons during the summer rainy season, which goes down to 125 cm during drier months (Soil Survey Staff, 1996). Rainfall that infiltrate into the soil during high water table conditions can move laterally, transporting P to surface drainage ditches (Burgoa et al., 1991; Mansell et al., 1991). Under this condition, water soluble P, the most labile form of P, is prone to lost via subsurface lateral flow before reaching the spodic horizon, where a P retention capacity exist..

Mehlich-1 P Concentrations

In Alachua, the Mehlich-1 P concentrations at 0 – 5 cm depth for the silvopasture and treeless pasture were 97 and 104 mg kg^{-1}, respectively. Corresponding values for the Suwannee, Manatee, and Osceola fields were 9 and 11 mg kg^{-1},5 and 6 mg kg^{-1} (Tables 4-1 and 4-2 and Figures 4-3 and 4-4). Mehlich-1 soil test values for both the silvopasture and the treeless pasture in Alachua and the treeless pasture in Suwannee fell within the high (31-60 mg kg^{-1}) to the very high range (>60 mg kg^{-1}) as suggested by UF/IFAS Mehlich-1 soil-test interpretation for agronomic crops (Kidder et al., 2002). In contrast, Mehlich-1 P concentrations in the silvopasture sites Suwannee and in both pasture systems in Manatee and Osceola fell generally in the very low range. No difference in Mehlich-1 P concentration was observed between the two pasture systems ($\alpha = 0.05$) in

Alachua at 0 – 5, 5 – 15, and 15 – 30 cm depths. However, the treeless pasture had higher P values at the 30 – 50, 50 – 75, and 75 – 100 cm depths. For the Suwannee site, Mehlich-1 P values below 30 cm were lower for silvopasture systems, which is indicative of the slash pine “nutrient-capture” effect.

In general, no difference was observed between the two pasture systems at the Manatee and Osceola sites while the overall Mehlich-1 P levels at the sites was ten fold lower compared to Alachua and Suwannee. Presence of perched water table above the spodic soil layers enhances lateral P loss before it can reach the Bh horizon. In this case, the low P retention capacity of the A and E horizons, will control overall P movement. There is a need for further research to quantify the different nutrient pools in these agroforestry systems. Establishing long-term on-farm runoff plots and in-site wells monitoring will confirm the effectiveness of these agroforestry systems in reducing nutrient loss.

Results from the current study showed that the Ultisols (Alachua and Suwannee) had greater Mehlich-1 P concentration then Spodosols (Osceola and Manatee) in the upper soil layers (up to 50 cm of depth) [Table 4.3]. This is consistent with the higher Al and Fe concentrations in the upper soil layers of Ultisols (compared to Spodosols), which increase the P sorption capacity of these soils (see Chapter 3). This is also consistent with the characteristics of Spodosols, having a sandy A and E horizons with poor sorption capacities while the spodic horizon has much greater capacity for P retention (Mansell et al., 1991). Chen and Lena (2001) reported that P values in undisturbed Florida surface soils were as follows: Histosols>Inceptisols>Mollisols>Entisols>Alfisols>Spodosols.

Average values for Mehlich-1 P concentrations from the present study for the Alachua, Suwannee, Osceola and Manatee sites were, respectively, 100, 50, 10 and 6 mg kg^{-1} at depth 0 – 5 cm and 125, 7, 5, and 7 at depth 50 – 75 cm in the present study (Table 8-3). Nair and Graetz (2002) reported Mehlich-1 P concentrations of 14.9, 2.3, 5.2 and 8.1 respectively in the A, E, Bh, and Bw soil horizons of a beef pasture site (Spodosols) in the Okeechobee County of Florida.

Nitrate and Ammonium-N Concentrations

In Alachua, nitrate concentrations at 0 – 5 cm soil depth were 0.7 and 4.2 mg kg^{-1} respectively, in the silvopasture and the treeless pasture. Corresponding values for Suwannee were 1.9 and 10.8 compared to 0.8 and 0.0 in Manatee, and values of 2.0 and 0.2 for the Osceola site (Tables 4-1 to 4-2 and Figures 4-5 and 4-7). Ammonium concentrations in the 0 – 5 cm soil depth were 13.5 and 16.7, respectively, in the silvopasture and treeless pasture in Alachua, and 10.5 and 6.0 in Suwannee, 13.6 and 14.0 in Manatee, 2.3 and 2.2 in Osceola (Tables 4-1 to 4-2 and Figures 4-6 and 4-8). In Suwannee higher nitrate-N concentration was found in the treeless pasture as compared to the silvopasture at 0 – 5, 50 – 75, and 75 – 100 cm depths, whereas the ammonium-N concentration was only different at 0 – 5 cm depth.

Contrary to our expectations, no nitrate- and ammonium-N concentrations were generally observed among the pasture systems in Alachua, Osceola and Manatee. Nitrate and ammonium-N levels were generally very low, sometimes below the detection level. For a similar study in a pecan (*Carya illinoensis*) + cotton (*Gossypium hirsutum*) alley cropping system on Ultisols in northwestern Florida, Allen et al. (2003) reported a 34% reduction in nitrate concentration in the soil solution at 0.9 m depth when pecan and cotton roots were not separated by a root barrier compared to the “root-barrier” treatment., suggesting the potential safety net role of pecan roots. It is difficult to account for nitrate in most soil. Nitrate, a negatively charged ion, is not retained by the adsorbing complex of the soil and thus is very prone to leaching. Concentrations of these labile N species are in constant flux. It is also important to bear in mind that most soil ammonium will be transformed biologically to nitrate within 2 to 3 weeks at soil temperatures in the 75° to 90° F range (Boman and Obreza, 2002). Another avenue for potential nitrate losses in soil with highly fluctuating water table such as Spodosols (Osceola and Manatee) is denitrification. Under anaerobic conditions, nitrate is transformed into gaseous forms and lost to the atmosphere. Also, the nitrate-N could have moved laterally from the soil via subsurface flow.

Conclusions

In spite of the limitations of the study, the results show that silvopastures sites had lower P levels in the soil profile than treeless pastures suggesting that there is a tree effect. Silvopasture will increase the nutrient stock in the plant system following enhanced total nutrient uptake by trees and associated forage species, compared to the shallow-rooted forage species. The amount of P that could be transported to surface water will thus be reduced in the silvopstoral system. Although a similar trend was observed in the case on nitrogen, the differences between the two systems were less striking, possibly because of the difficulties in measuring the highly dynamic soil nitrogen levels.

Table 4-1. Mean values of water soluble P (WSP), Mehlich-1 P (M-1 P), and nitrate and ammonium-N concentrations for different soil layers of soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Alachua and Suwannee Florida, USA.

	Alachua			Alachua			Alachua		
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	*P*
Depth (cm)	WSP (mg kg^{-1})		*P*	M-1 P (mg kg^{-1})		*P*	NO_3 (mg kg^{-1})		
0-5	5.6	10.9*	0.0001	96.5	104.1	0.7011	0.7	4.2	0.0960
5-15	2.8	8.5*	0.0001	99.5	125.8	0.1602	0.3	0.8	0.3358
15-30	1.9	7.9*	0.0001	83.6	108.6	0.1669	0.2	0.3	0.4404
30-50	1.7	7.3*	0.0001	61.4	125.4*	0.0079	0.1	0.2	0.2271
50-75	1.5	6.2*	0.0001	49.1	171.9*	0.0001	0.0	0.0	0.1059
75-100	1.4	6.7*	0.0001	49.6	200.4*	0.0001	0.0	0.1	0.2345
	Alachua			Suwannee			Suwannee		
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	*P*
Depth (cm)	NH_4 (mg kg^{-1})		*P*	WSP (mg kg^{-1})		*P*	M-1 P (mg kg^{-1})		
0-5	13.5	16.7	0.1742	4.1	10.1*	0.0001	8.6	90.6*	0.0001
5-15	7.1	7.0	0.9443	1.2	6.4*	0.0001	17.0	88.0*	0.0001
15-30	3.5	5.2	0.0730	0.6	4.6*	0.0001	11.0	72.5*	0.0001
30-50	3.1	4.1	0.1282	0.4	2.9*	0.0001	6.0	42.6*	0.0001
50-75	2.4	3.1	0.0732	0.3	1.7*	0.0001	3.4	19.7*	0.0001
75-100	2.4	2.8	0.4612	0.2	1.5*	0.0001	2.6	11.6*	0.0001
	Suwannee			Suwannee					
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture				
Depth (cm)	NO_3 (mg kg^{-1})		*P*	NH_4 (mg kg^{-1})		*P*			
0-5	1.9	10.8*	0.0028	10.5*	6.0	0.0149			
5-15	0.3	3.0*	0.0001	3.7	4.3	0.3138			
15-30	0.1	1.08*	0.0001	2.7	2.5	0.5804			
30-50	0.1	0.9*	0.0001	2.9	2.2	0.0765			
50-75	0.0	0.7*	0.0050	1.9	2.3	0.1599			
75-100	0.1	0.7*	0.0298	2.4	2.0	0.3726			

[(*Indicates significant P values within a given depth ($p<0.05$))]

Table 4-2. Mean values of water soluble P (WSP), Mehlich-1 P (M1-P), nitrate, ammonium concentrations of different soil layers for soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Manatee and Osceola, Florida, USA.

	Manatee			Manatee			Manatee		
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	WSP (mg kg-1)		*P*	M-1 P (mg kg-1)		*P*	NO3 (mg kg-1)		*P*
0-5	11.4	23.4*	0.0009	8.9	10.9	0.1796	0.8	0.0	0.3097
5-15	1.43	4.60*	0.0419	0.7	1.5*	0.0006	0.8	0.0	0.2583
15-30	0.30	0.60*	0.0001	0.2	0.1	0.4311	0.5*	0.0	0.0203
30-50	0.10	0.43*	0.0001	0.0	0.3	0.1472	0.2*	0.0	0.0282
50-75	0.04	0.33*	0.0001	1.0	3.3*	0.0095	0.7*	0.3	0.0150
75-100	0.05	0.95*	0.0002	2.3	8.1*	0.0006	0.2	0.2	0.5636
	Manatee			Osceola			Osceola		
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	
Depth (cm)	NH4 (mg kg-1)		*P*	WSP (mg kg-1)		*P*	M-1 P (mg kg-1)		*P*
0-5	13.6	14.0	0.9024	6.8	11.0*	0.0352	5.0	6.1	0.1213
5-15	3.4	4.0	0.3212	1.4	1.4	0.9548	1.7	1.9	0.7390
15-30	2.8	2.0	0.3035	1.0*	0.5	0.0208	1.4*	0.5	0.0487
30-50	1.5	1.5	1.0000	0.7*	0.3	0.0320	3.9	1.0	0.1009
50-75	1.4	1.6	0.3156	0.6	0.4	0.1360	7.1*	2.3	0.0405
75-100	2.0	1.8	0.5706	0.9*	0.5	0.0164	11.5*	2.7	0.0002
	Osceola			Osceola					
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture				
Depth (cm)	NO3 (mg kg-1)		*P*	NH4 (mg kg-1)		*P*			
0-5	2.0*	0.2	0.0068	2.3	2.2	0.4956			
5-15	0.8	0.6	0.6081	12.4	10.5	0.0152			
15-30	1.7	0.5	0.0786	5.0	5.8	0.3807			
30-50	3.0	0.3	0.1011	3.1	3.3	0.3391			
50-75	0.3	0.2	0.3369	3.0	2.5	0.4652			
75-100	0.4	0.1	0.1876	2.1	2.1	0.1421			

[(*Indicates significant P values within a given depth (p<0.05)]

Table 4-3. Mean values of Mehlich-1 extractable-P (M1-P) concentrations for soil profiles of the Spodosols (Osceola and Manatee) and Ultisols (Alachua and Suwannee) in Florida.

Depth (cm)	Alachua	Suwannee	Manatee	Osceola
0-5	100a	50b	10c	6c
5-15	113a	52b	2c	1c
15-30	96a	42b	1c	0.1c
30-50	93a	24b	3c	0.2c
50-75	111a	12b	2b	5b
75-100	125a	7b	5b	7b

*Means separation by Waller-Duncan procedure. Mean values of soil characteristics within a given depth followed by the same letter are not different ($p<0.05$)

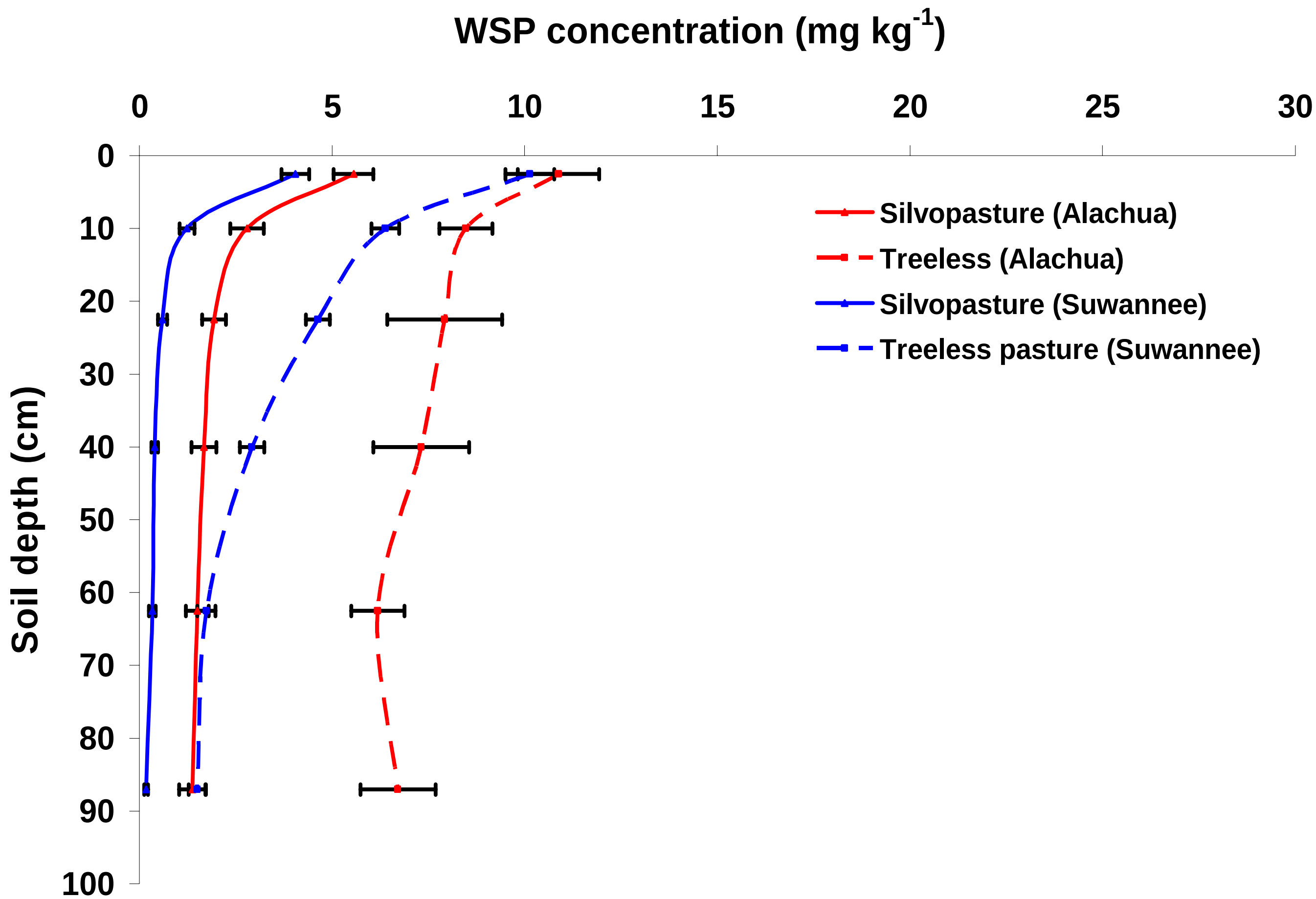

Figure 4-1. Water soluble P (WSP) concentration at different soil layers for silvopasture and treeless pasture at the Alachua and Suwannee field sites featuring Spodosols. Error bars indicate standard errors (n = 24).

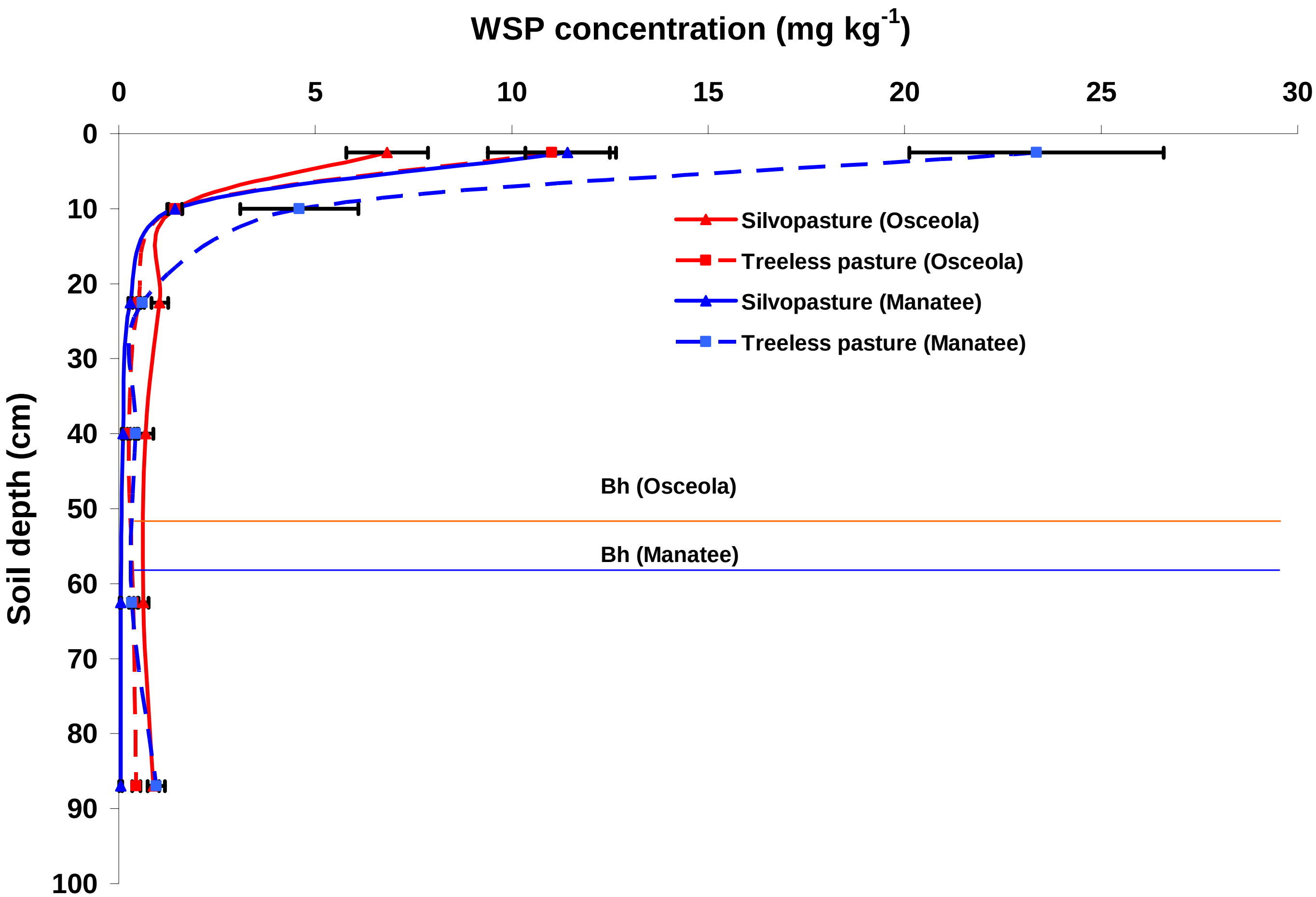

Figure 4-2. Water soluble P (WSP) concentration by depth in the silvopasture and treeless pasture sites in Osceola and Manatee. Error bars designate standard errors.

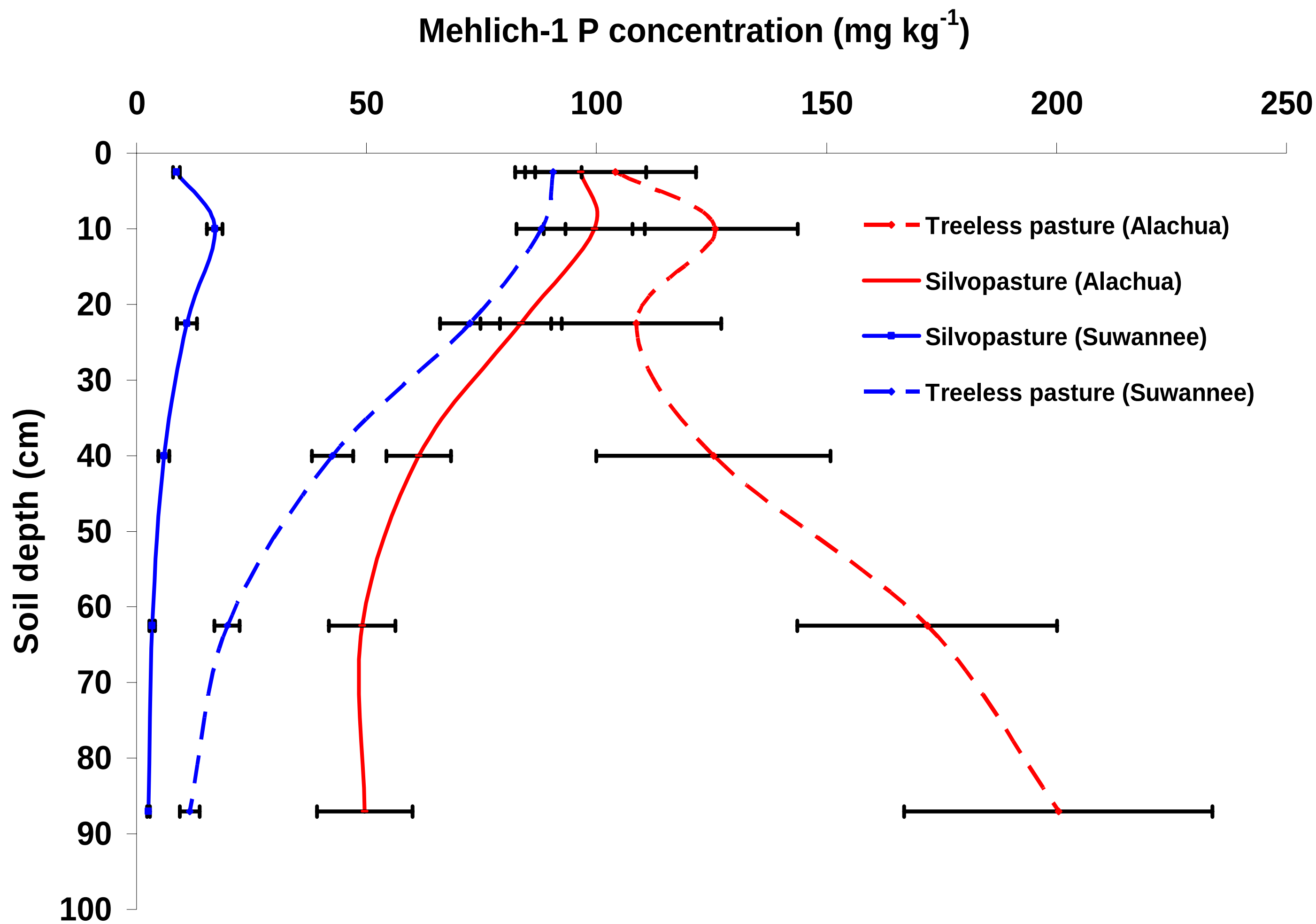

Figure 4-3. Mehlich-1 P concentration by depth in the silvopasture and treeless pasture sites in Alachua and Suwanneee. Error bars designate standard errors.

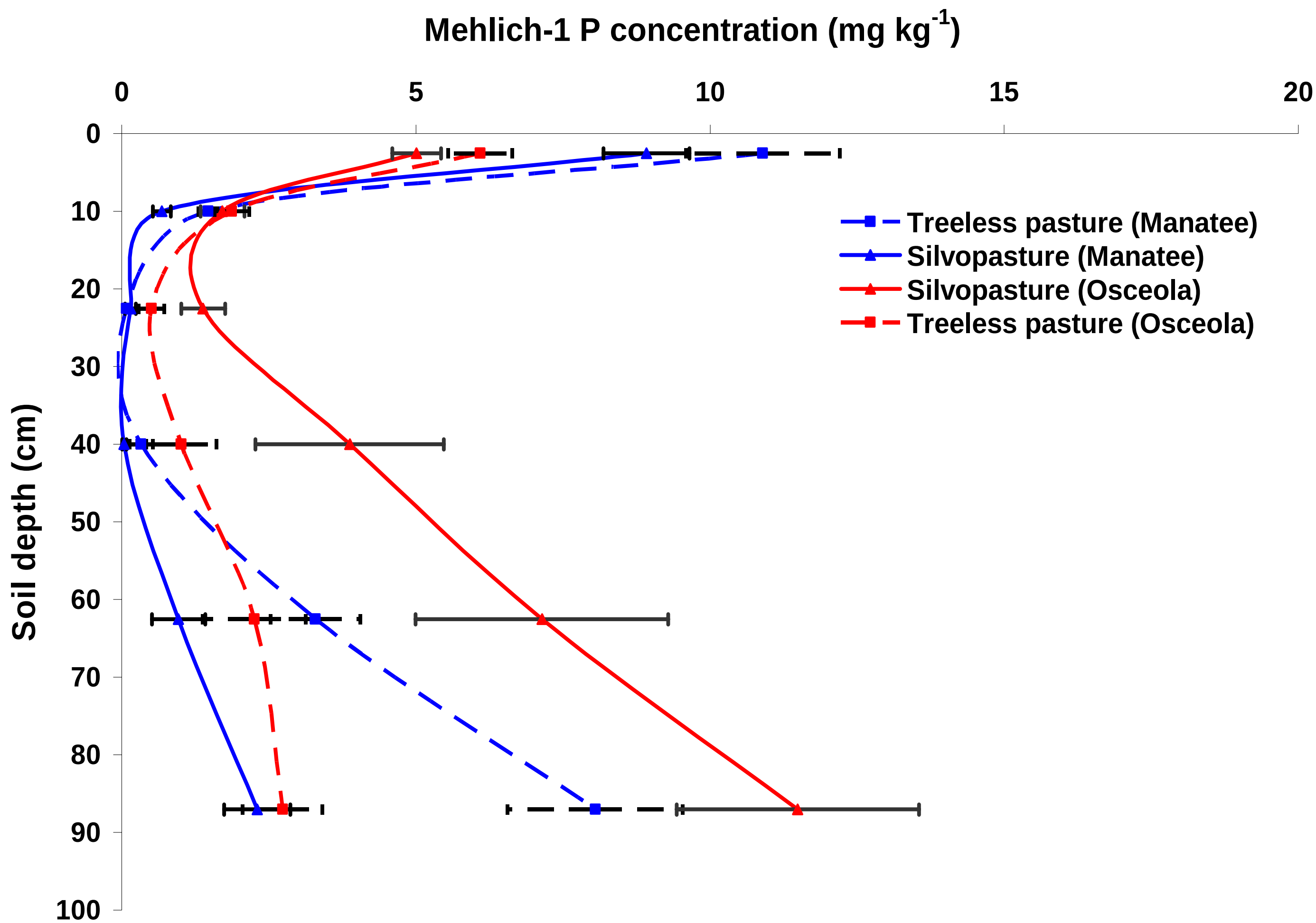

Figure 4-4. Mehlich-1 P concentration by depth in the silvopasture and treeless pasture sites in Osceola and Manatee. Error bars designate standard errors.

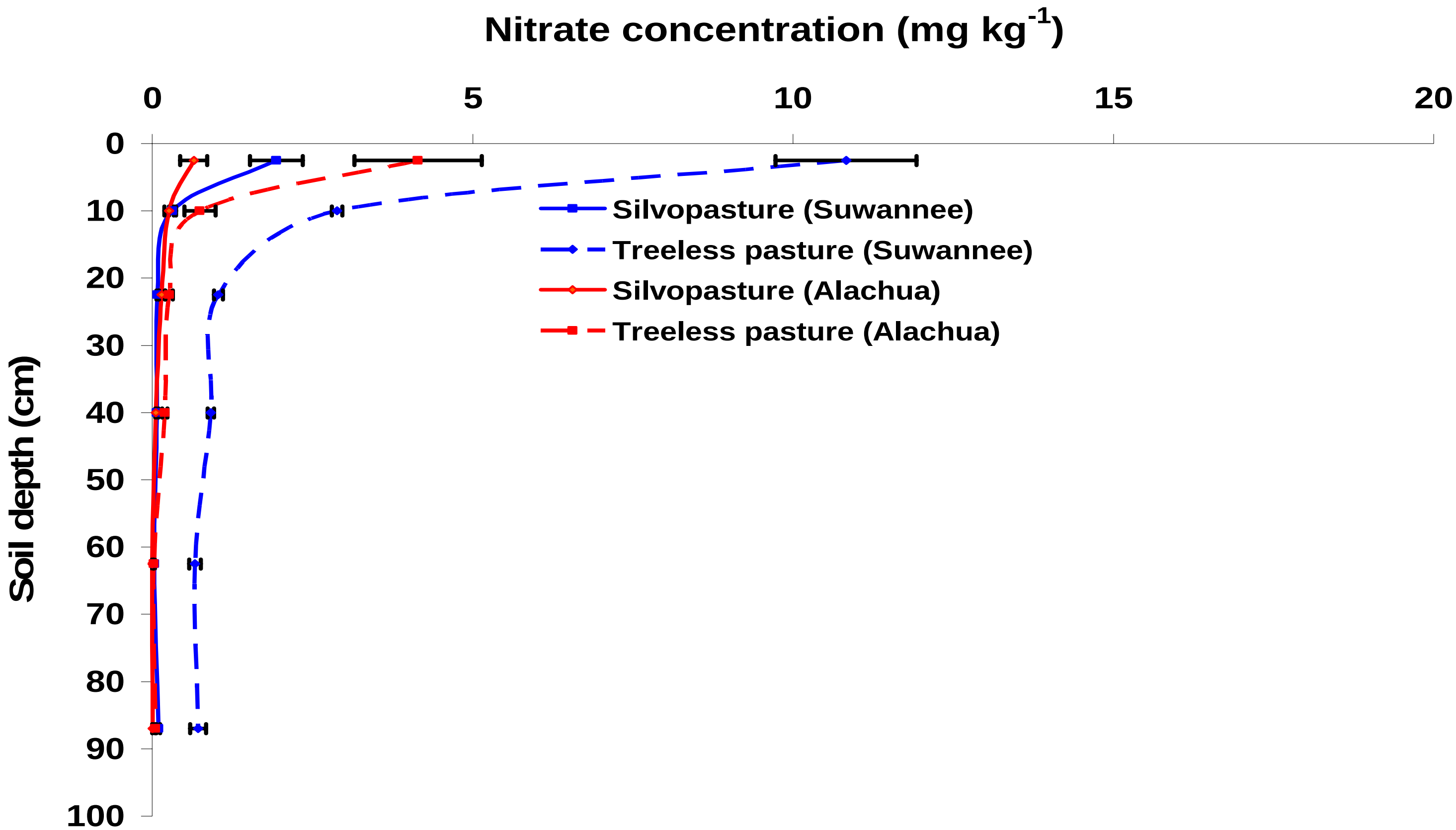

Figure 4-5. Nitrate concentration level by depth in silvopasture and treeless pasture sites in Alachua and Suwannee on Ultisols. Error bars designate standard errors.

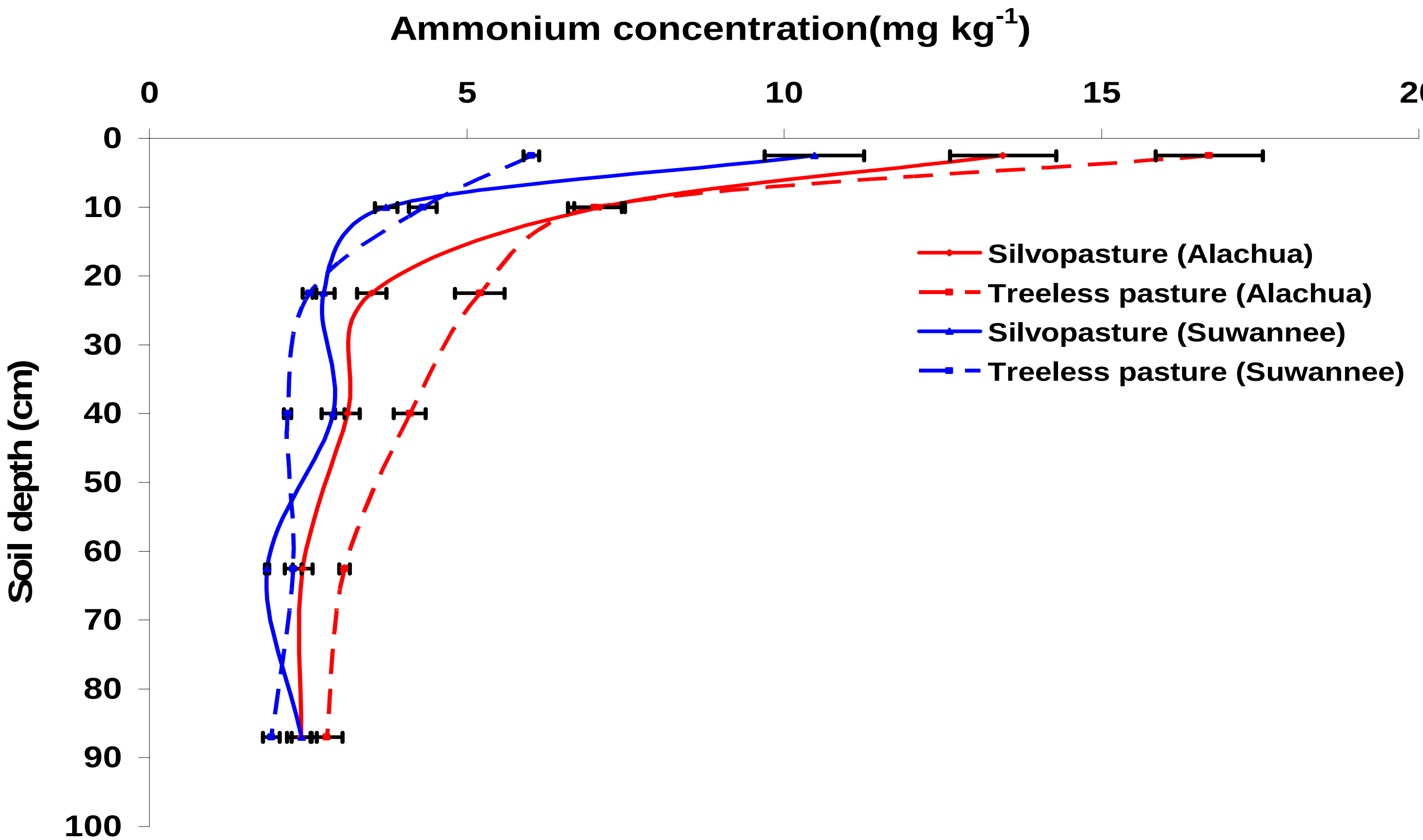

Figure 4-6. Ammonium-N concentrations levels by depth in silvopasture and treeless pasture sites in Alachua and Suwannee (Ultisols sites). Error bars designate standard errors.

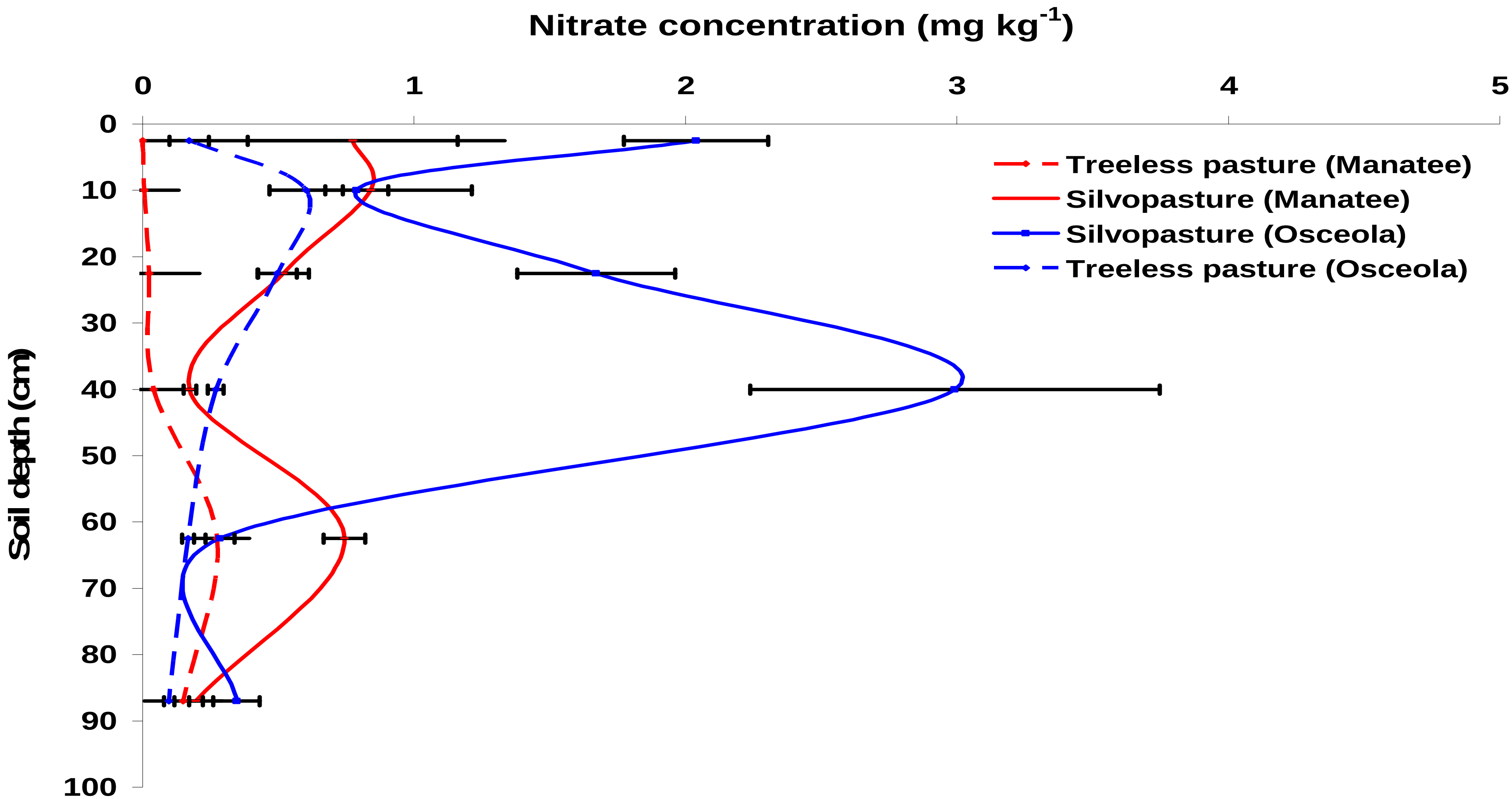

Figure 4-7. Nitrate-N concentration for different soil depth for silvopasture and treeless pasture systems for filed sites in Manatee and Osceola (Spodosols). Error bars designate standard errors.

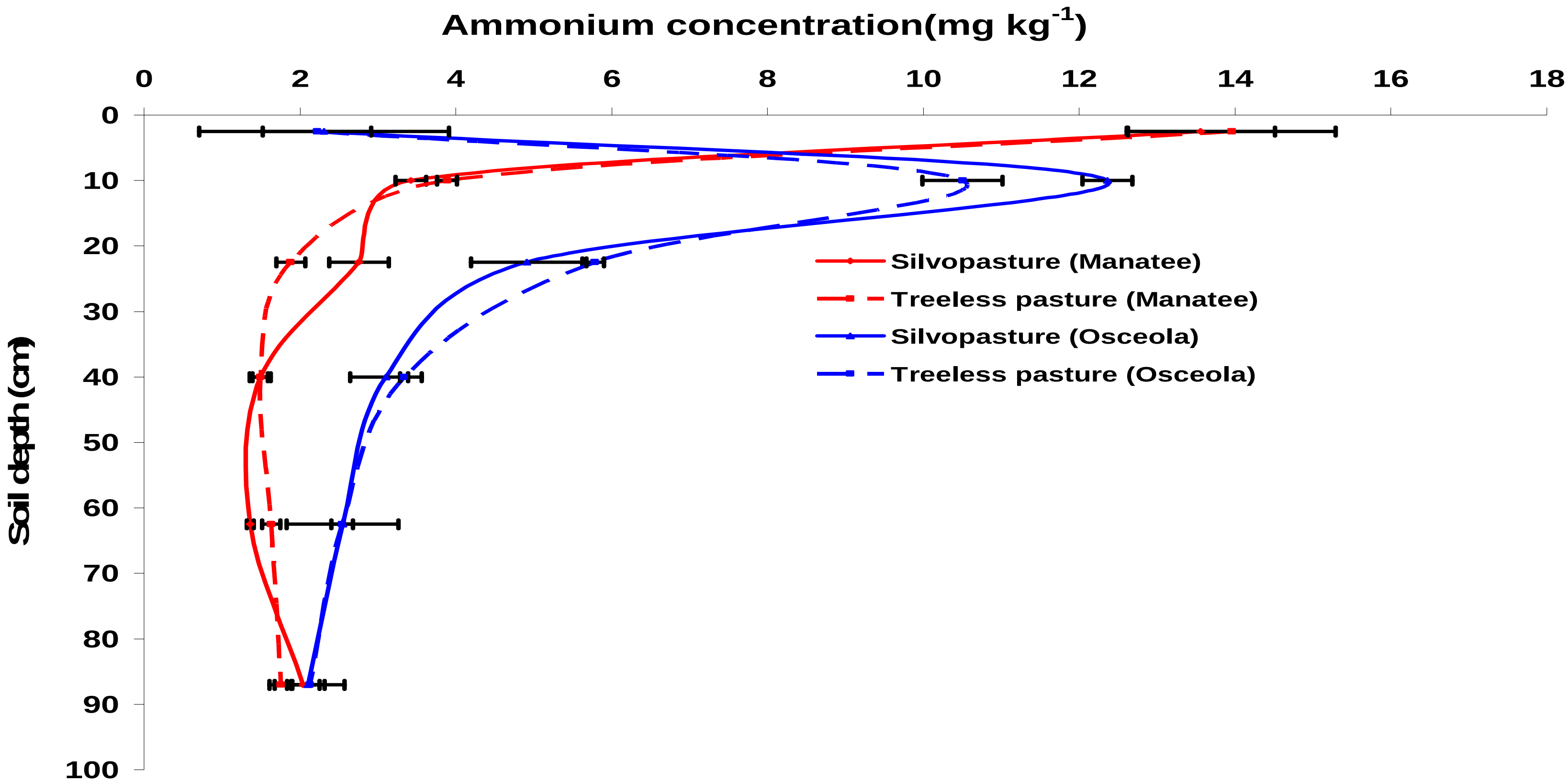

Figure 4-8. Ammonium-N concentrations levels for different soil depth in silvopasture and treeless pasture sites in Manatee and Osceola on Spodosols. Error bars designate standard errors

CHAPTER 5
SOIL PHOSPHORUS STORAGE CAPACITY UNDER A SLASH PINE (*Pinus elliottii*) + BAHIAGRASS (*Paspalum notatum*) SILVOPASTURE AND A TREELESS PASTURE

Introduction

Phosphorus loss from farmlands has been identified as one of the main causes of eutrophication of fresh water bodies. Phosphorus loading of water bodies associated with runoff from operations and heavy manuring of pasturelands in soils is a serious environmental concern. The incorporation of trees in pastures could enhance P storage in the soil-plant system (Nair and Graetz, 2004; Nair and Kalmbacher, 2004; Jose et al., 2004; Chapter 4 of the present study). Silvopasture, the intentional combination of trees, forage plants and livestock into an integrated, intensively-managed system (Nair, 1993; Garrett et al., 2000; Nair et al., 2004) is potentially a promising land-use system to enhance the economic returns of forestry operations (Lundgren et al., 1983; Lewis et al, 1985; Dangerfield and Harwell, 1990; Clason, 1995; Grado et al., 2001; Stainback and Alavalapati, 2004).

Studies on tropical agroforestry systems in nutrient-depleted soils have demonstrated the capacity of deep rooted trees to absorb nutrients that have leached below the rooting zone of agronomic crops, and recycle these nutrients through litterfall and rootfall in the crop-root zone, thus improving the nutrient-use efficiency in the system as a whole (Young, 1997). In addition, the longer lifespan of tree roots help capture nutrients such as nitrate and phosphorus before and after the crop is planted and harvested (Jose et al., 2004). This would enhance the overall resource-use efficiency of the system (van Noordwijk et al., 1996).

Research conducted in temperate agroforestry systems have showed similar results. In a study conducted in pecan (*Carya illinoensis* K. Koch)–cotton (*Gossypium hirsutum* L.) alley cropping system in northwestern Florida, Allen et al. (2003) reported a 34% reduction in nitrate nitrogen concentration in the soil solution at 0.9 m depth when pecan and cotton roots were not separated by a root barrier compared to the root barrier treatment, suggesting the potential safety-net role of pecan roots. The nutrient interception capacity of riparian buffer is another example of the safety-net concept. Riparian buffer strips offer a means of removing non-point source pollutants from farmlands (Addy et al., 1999; Bharati et al., 2002; Lee et al., 2003; Schultz et al., 2004). Lee et al. (2003), in a study undertaken in central Iowa, Midwestern United States, reported that a switch grass (*Panicum virgatum*)-woody buffer treatment removed 85% nitrate-N, and 80% of the phosphate-P in the runoff. Including a woody component in the buffer strip enhanced the uptake effectiveness of soluble nutrients by over 20%. According to Anbumozhi et al. (2005) forested buffers reduced agricultural nutrient losses from livestock activities in adjacent uplands in surface stream waters in the Tokachigawa watershed in Japan. In another study conducted in several European countries significantly higher N uptake from forested sites as compared to herbaceous sites was observed (Hefting et al., 2005).

Despite the fact that the ‘safety-net’ concept is important to enhancing nutrient use efficiency and improving crop production under tropical ecological settings, it has another application in the heavily fertilized and sandy soils of Florida (Nair and Graetz,

2004) that have low nutrient retention capacities. The capacity of tree roots to capture nutrients from the deeper soil horizons can enhance nutrient storage in the plant-soil system and therefore reduce the amount of nutrients that might otherwise be transported to ground and surface water through runoff and leaching and thus cause non-point-source pollution of these water bodies.

Environmental indicators of P loss such as soil test P (STP) or degree of P saturation (DPS) do not allow any assessment of the capacity of a soil to retain future addition of P (Nair and Harris, 2004). To address this shortcoming, these authors proposed a DPS-based calculation of the remaining "Soil P Storage Capacity (SPSC)". This index takes into account both the risks attributed to prior loading and the inherent, limited P sorption capacity of a soil. The SPSC offers a direct estimate of the amount of P a given soil can hold before exceeding a threshold soil concentration, consequently, resulting in water pollution.

Generally, the P sorption maximum of a soil is determined by using the Langmuir adsorption equation (Nair et al., 1998), which is a complex and time-consuming method. Another way of estimating the soil P storage capacity of a soil is to use a single point isotherm (or one point) value. Simple measurements of a single-point isotherm were shown to reasonably estimate P sorption capacities of soils (Harris et al., 1996; Indiati et al., 2002; Nair and Graetz, 2002; Lu and O'Connor, 2004).

The objectives of this study were to (i) assess differences in SPSC estimates in the surface and subsurface horizons in soil profiles of two pasture systems (silvopasture and treeless pasture) at four locations including two different soil orders in Florida, and (ii) assess differences in SPSC estimates using two methods (Mehlich-1 and single-point isotherm).

Material and Methods

Site Description

An on-farm research was undertaken in Osceola (28^0 9' N, 81^0 10' W), Manatee (27^0 13' N, 82^0 8' W), Suwannee (30^0 24' N, 830 0' W), and Alachua (29^0 45' N, 82^0 33' W) counties in Florida. The silvopastoral systems consisted of a slash pine (*Pinus elliottii*)–bahiagrass (*Paspalum notatum*) and the treeless pasture consisted only of bahiagrass. A grid sampling procedure was used to collect 24 soil profiles from each site at each location during summer and fall 2004. The soil samples were collected at six depths: 0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75 and 75 – 100 cm. The soils in both Alachua and Suwannee are Ultisols, whereas those in Manatee and Osceola counties are Spodosols. Refer to Chapter 3 for more in-depth details on the site description. Refer to chapter 3 for an in depth description of the sites characteristics.

Statistical Procedures

The statistical analyses were performed using SAS PROC ANOVA (SAS 8.2 for Windows). The experimental design used was a 4-fold nested model (see Chapter 3). The regression analyses were performed using SAS PROC REG and PROC GLM (SAS 8.2 for Windows).

Calculations of Parameters

Soil P storage capacity calculated with Mehlich-1

The phosphorus saturation ratio (PSR) was computed as the molar ratio of Mehlich1-P and Mehlich1-Fe and Al (Nair et al., 2004). The PSR formula is as follows:

PSR = (Mehlich-1 P ÷ 31) ÷ ((Mehlich-1 Fe ÷ 55.8) + (Mehlich-1 Al ÷ 27))

The soil phosphorus storage capacity (SPSC) was calculated as:

SPSC = (0.15 – PSR) * ((Mehlich-1 Fe ÷ 55.8) + (Mehlich-1 Al ÷ 27)) * 31 (mg P kg^{-1})

(Nair and Harris, 2004)

The SPSC, is thus an estimate of the amount of P that can safely be applied to a soil up to a defined depth before the soil poses an environmental risk. The SPSC values were then calculated on a kg ha^{-1} basis (for a specified depth) assuming a bulk density of 1500 kg m^{-3} (Nair and Harris, 2004). For the calculation of SPSC, the choice of PSR instead of DPS was made solely for simplicity purpose. The SPSC of the soil was based on a threshold PSR of 0.15. According to Nair et al. (2004), the value of 0.15 used in the SPSC calculation is the best approximation available to date of the PSR value corresponding to the critical P solution concentration of 0.10 mg P L^{-1} as proposed by Breeuwsma and Silva (1992).

Soil P storage capacity calculated with Single Point Isotherm Data

The single point isotherm was determined following the procedure described in Figure 5-1and using 4 sampling points from each study site. With eight plots, each with 4 sampling points and six depths, a total of 192 soil samples were used for the analysis.

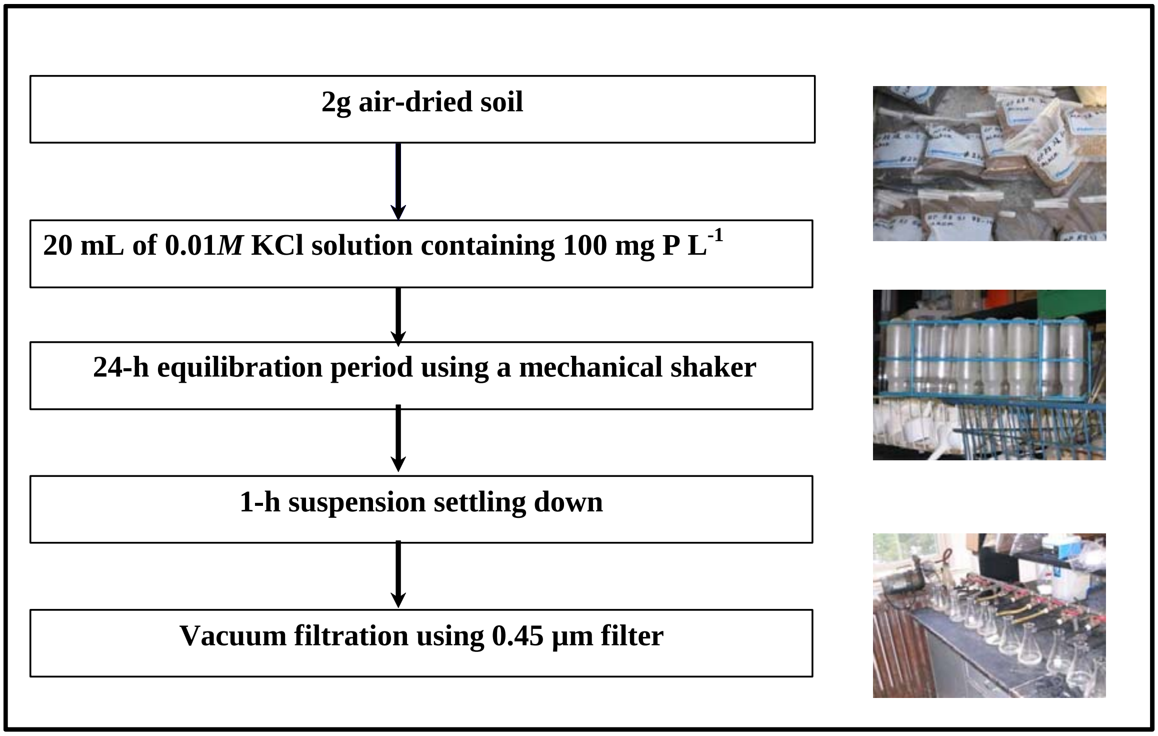

Figure 5-1. Determination of P sorption capacity using a single point isotherm based on a procedure by Nair et al. (1998).

The filtrate was then analyzed for P using the Murphy-Riley procedure (Murphy and Riley, 1962). Following the single point isotherm determination, the phosphorus sorption was determined by subtracting the P added to the P in solution. The PSR and SPSC determined by the single point isotherm were then calculated using the following formulas:

(i) PSR = Melhich-1 P ÷ (P sorption + Mehlich-1 P)

(ii) SPSC = (0-15 – PSR) * (P sorption + Mehlich-1 P) (mg P kg^{-1})

When the SPSC becomes negative, i.e. PSR > 0.15, the soil is considered to be a net source of P source.

Results and Discussion

Phosphorus Saturation Ratio

Phosphorus saturation ratios for the 0 – 5 cm soil depth in the silvopasture and treeless pasture in Alachua were 0.17 and 0.19, respectively. Corresponding values for the Suwannee site were 0.05 and 0.93, compared to 0.15 and 0.22 (Manatee), and 0.06 and 0.45 in Osceola (Table 5-1). These findings suggest that the surface soils under treeless pasture have a greater potential to release P irrespective of the location or the soil order of the land use. Concentrations of Water Soluble P (WSP) (Chapter 4) also indicate higher values in the surface soils for treeless pasture compared to silvopasture, therefore supporting the PSR results. Results of the study showed differences between the silvopasture and treeless pasture systems at the 50 – 75, 75 – 100 cm soil depth in Alachua, with the treeless pasture having the highest PSR values. In Osceola PSR values were similar between the two systems for all sampling depths. In Manatee and Suwannee, differences were observed between the two pasture systems throughout the soil profile. The silvopasture sites showed lower PSR values than the treeless pasture sites, indicative of a tree effect. This is consistent with the results from the water soluble P and the Mehlich-1 P analysis obtained at the same study sites (see Chapter 4 for details).

Results of the study showed lower PSR values in the Spodosols as compared to the Ultisols from depth 15 – 30 to 50 – 75 cm (Table 5-2). The lower PSR values observed in the Spodosol sites may be attributed to a low soil Mehlich-1 P associated with Spodosols characterized by a highly fluctuating and perched water tables resulting in subsurface lateral flow in the upper soil layers which have the low P sorption capacities. As a result, appreciable P losses will occur since drainage water may not pass through the spodic horizon which has a high P retention capacity and may function as a P filter (Campbell, 1995).

Relationships between WSP and PSR for the soil surface (0 – 5 and 5 – 15 cm depths) of the study sites at the four locations are shown in Fig. 5-2. The regression analysis showed that the cubic model had the highest r-squared ($r^2 = 0.33$) [Appendix] but for practical reason the linear equation was chosen ($r^2 = 0.31$). The low r-square observed for the relation is mainly due to site variations, in particular from Alachua sites which have shown evidence of the presence of phosphatic materials. Figure 5.2 shows a possible changing point at a PSR value between 0.05 and 0.10 where the WSP sharply increases. Nair et al. (2004), indicated a PSR of 0.15 as a threshold PSR at which a sharp increase in WSP can occur in the A horizon and subsurface horizons in Florida Spodosols.

Soil Phosphorus Storage Capacity

Remaining soil P storage capacity at 0 – 5 cm depth for the silvopasture and treeless pasture in Alachua were -14.3 and -13.6 kg ha^{-1} respectively. Corresponding values were 15.75 and -43.66 in Suwannee, 0.6 and -2.5 in Manatee, and 26.2 and 14.1 in Osceola (Table 5-1). Results of the study showed significant differences between the silvopasture and treeless pasture systems at depth 50 – 75, 75 – 100 cm in Alachua with the treeless pasture having the lowest SPSC values. In Osceola, no differences were observed throughout the soil profile. In Manatee no differences were observed between the two pasture systems at 30 – 50 and 50 – 75 cm depths. In Suwannee SPSC values were consistently higher for silvopasture systems throughout the entire soil profile.

The highly negative SPSC found in the deeper soil horizons in Alachua sites may be explained by the presence of phosphatic materials in the deeper sampling depths of the sites (Table 5-1). Ramnarine (2003) identified phosphatic soils in Alachua County, Florida. These soils showed an increase in total phosphorus (TP) with depth, which is different for most nonphosphatic soils.

At the Suwannee site total SPSC to one meter depth in the silvopasture and treeless pasture were 337 and -59 P kg ha^{-1} respectively. Corresponding values for the Manatee site were 329 and 191 kg P ha^{-1} compared to 657 and 926 kg P ha^{-1} in Osceola), and values of -36 and -542 kg ha^{-1} in Alachua (Table 5-3). Differences between the two pasture systems were significant for the Alachua, Suwannee and Manatee sites (Table 5-3).

In general, the capacity of the soil to store additional P was lower in the treeless pasture sites as compared to silvopasture sites (Figure 5-3). These findings along with the results of the water soluble P (WSP) analysis (Chapter 3) suggest that the chances for P to move out of the soil are greater under treeless pasture than under silvopasure, a tree-based system. The "bulge" in the graph for the Spodosol in Osceola (Figure 5-4) corresponds to the sandy E horizon at the 30 – 50 cm depth where the storage capacity of the soil (calculated from a low PSR resulting from a low detectable Mehlich-1 P for the reason explained earlier) would result in erroneous calculations for SPSC.

Estimation of Mehlich-1-based Soil P Storage Capacity (SPSC-M1) and Soil P Storage Capacity-Single Point Isotherm (SPSC-ISO)

Results from the study sites showed that SPSC values determined with Mehlich-1 were lower than that of the single point isotherm method (Figure 5-5). In other words, soil P storage capacity was underestimated when the Mehlich-1 method was used, as opposed to the single point isotherm. This is consistent with a study by Chrysostome (2005), who found that the Mehlich-1 method underestimated SPSC compared to the oxalate method. In this study Mehlich-1 Fe and Al concentrations and oxalate extractable

Fe and Al concentrations were respectively 13 and 129 mg kg^{-1} vs. 268 and 327 mg kg^{-1}, respectively.

Even though Mehlich-1-based soil P storage capacity and SPSC-ISO give different values, they are nevertheless correlated. The regression analysis showed that the cubic model had the highest r-squared ($r^2 = 0.57$) [Appendix] but for practical reason the linear equation was chosen ($r^2 = 0.50$). The relationship between SPSC-M1 and SPSC-ISO (Figure 5-5) for the soil surface (0 – 5 and 5 – 15 cm depths) of the study sites is given by the following formula:

SPSC-M1 = 0.65 (SPSC-ISO) + 29.77; $r^2 = 0.50$, $p < .0001$

The general relationship indicates that the Mehlich-1 SPSC calculation method underestimates the remaining P storage capacity. The results are consistent with the findings of a research conducted by Chrysostome (2005) in which a comparison was made between SPSC calculated using Mehlich-1 and oxalate ($SPSC_{oxalate}$). The research concluded that $SPSC_{oxalate}$ resulted in a more accurate estimation of the remaining capacity of a soil to sorb P than Mehlich-1-based SPSC, because oxalate is a more powerful extractant than Mehlich-1 and extracts most of the reactive Al and Fe present in the soil and representing its P sorption capacity. Chrysostome (2005) recommended the use of a correction factor for Mehlich-1-based SPSC to compensate for the underestimation of the remaining capacity of the soil to adsorb additional P using this extractant. Several researchers (Harris et al., 1996; Indiati et al., 2002; Nair and Graetz, 2002; Lu and O'Connor, 2004) have observed reasonable estimations of the maximum soil P sorption capacity using the single point isotherm method and therefore, calculating

SPSC using this method is likely to be comparable to the oxalate determination. Further research is needed to validate this statement.

Conclusions

The presence of trees in pastures may reduce the chances of future additions of P to move out of the soil. This, in turn, suggests that silvopastoral systems would provide a greater environmental service in regards to water quality protection compared to treeless pastures under comparable ecological settings. The single point isotherm method seems to better estimate the remaining Soil P Storage Capacity as compared to the Mehlich-1 method.

Table 5-1. Mean values of phosphorus saturation ratio (PSR) and soil P storage capacity (SPSC) for soil profiles at the center of the alley of the silvopasture and a treeless pasture sites in Alachua, Suwannee, Manatee and Osceola, Florida, USA

	Alachua			Alachua			Suwannee		
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	*P*
Depth (cm)	PSR		*P*	SPSC (mg P kg^{-1})		*P*	PSR		
0-5	0.19	0.18	0.5904	-14.3	-13.6	0.9504	0.04	0.42	0.0099*
5-15	0.17	0.19	0.4309	-17.1	-38.0	0.3184	0.06	0.28	0.0257*
15-30	0.16	0.17	0.9199	-16.8	-30.6	0.6331	0.04	0.24	0.0168*
30-50	0.14	0.17	0.3228	7.4	-51.1	0.2256	0.03	0.16	0.0226*
50-75	0.14	0.22*	0.0005	6.7*	-207	0.0025	0.02	0.09	0.0012*
75-100	0.15	0.23*	0.0005	-4.4*	-260	0.0039	0.02	0.06	0.0048*
	Suwannee			Manatee			Manatee		
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture		Silvopasture	Treeless pasture	*P*
Depth (cm)	SPSC (mg P kg^{-1})		*P*	PSR		*P*	SPSC (mg P kg^{-1})		
0-5	16*	-44	0.0001	0.14	0.21*	0.0194	0.6*	-2.4	0.0115
5-15	44*	-61	0.0001	0.02	0.05*	0.0002	6*	4	0.0171
15-30	74*	-60	0.0001	0.01	0.01*	0.0200	7*	4	0.0365
30-50	81*	-6	0.0001	0.00	0.01*	0.0427	31	9	0.2653
50-75	83*	52	0.0211	0.00	0.02*	0.0195	108	83	0.2234
75-100	73	57	0.1203	0.01	0.04*	0.0001	175*	81	0.0002
	Osceola			Osceola					
	Silvopasture	Treeless pasture		Silvopasture	Treeless pasture				
Depth (cm)	PSR		*P*	SPSC (mg P kg^{-1})		*P*			
0-5	0.02	0.04*	0.0885	26.2	14.1	0.2491			
5-15	0.01	0.01	0.7654	45.3	41.2	0.8594			
15-30	0.01	0.00	0.8633	69.3	92.1	0.5666			
30-50	0.01	0.00	0.1284	144	406	0.0706			
50-75	0.02	0.00	0.0637	229	270	0.5318			
75-100	0.02	0.01	0.0724	234	227	0.8971			

(*Indicates significant P values within a given depth (p<0.05)].

Table 5-2. Mean values of phosphorus saturation ratio (PSR) for soil profiles of the Spodosols (Osceoala and Manatee) and Ultisols (Alachua and Suwannee) in Florida.

Depth (cm)	PSR			
	Alachua	Suwannee	Osceola	Manatee
0-5	0.18b*	0.48a	0.26ab	0.18b
5-15	0.17ab	0.27a	0.06bc	0.04c
15-30	0.16a	0.20a	0.01b	0.006b
30-50	0.15a	0.15a	0.009b	0.003b
50-75	0.17a	0.07b	0.01c	0.01c
75-100	0.17a	0.05b	0.03c	0.02bc

*Statistical analysis by Waller-Duncan procedure. Mean values of soil characteristics of silvopasture and treeless pasture within a given depth followed by the same letter are not significantly different ($p<0.05$).

Table 5-3. Cumulative soil P storage capacity (SPSC) for the 0-1 m soil depth at the center of the alley of the silvopasture and a treeless pasture sites in Alachua, Suwannee, Manatee and Osceola, Florida, USA.

Location	Treatment	SPSC (kg P ha^{-1})	*P*
Alachua			
	Silvopasture	-36	0.0186
	Treeless pasture	-542*	
Manatee			
	Silvopasture	329*	0.0051
	Treeless pasture	191	
Osceola			
	Silvopasture	657	0.2182
	Treeless pasture	926	
Suwannee			
	Silvopasture	342*	0.0001
	Treeless pasture	-60	

[(*Indicates significant P values (p<0.05)]

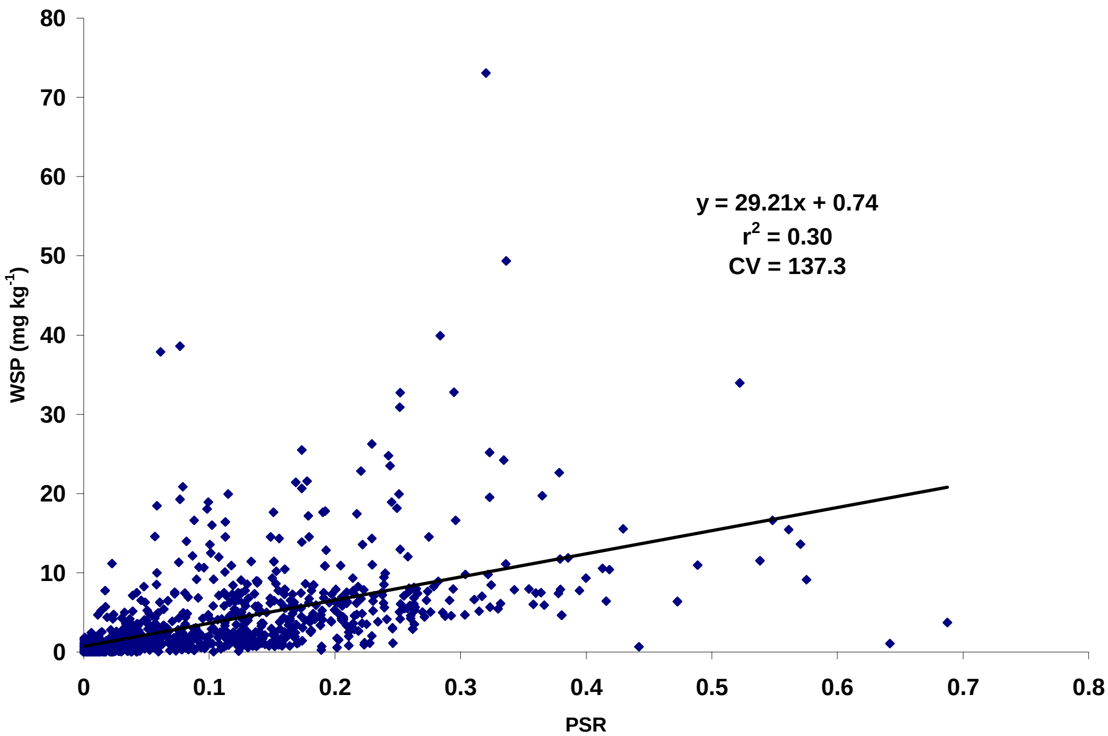

Figure 5-2. Relationship between phosphorus saturation ratio (PSR) and Water soluble P (WSP) for surface soils (0-5 and 5-15 cm) of the study sites in Florida

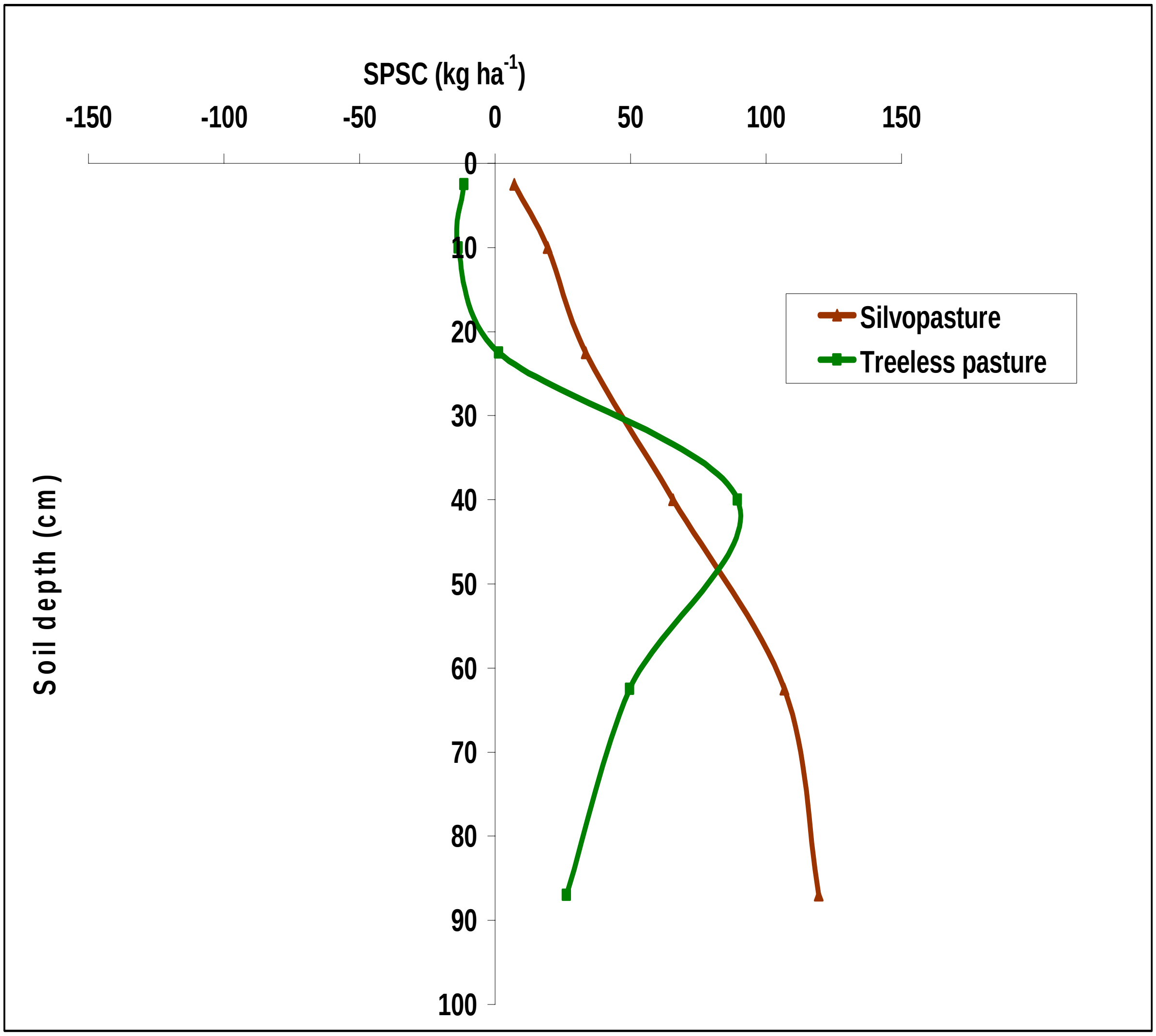

Figure 5-3. General trend in soil P storage capacity (SPSC) in the center of the alley of the silvopasture and a treeless pasture sites in Florida.

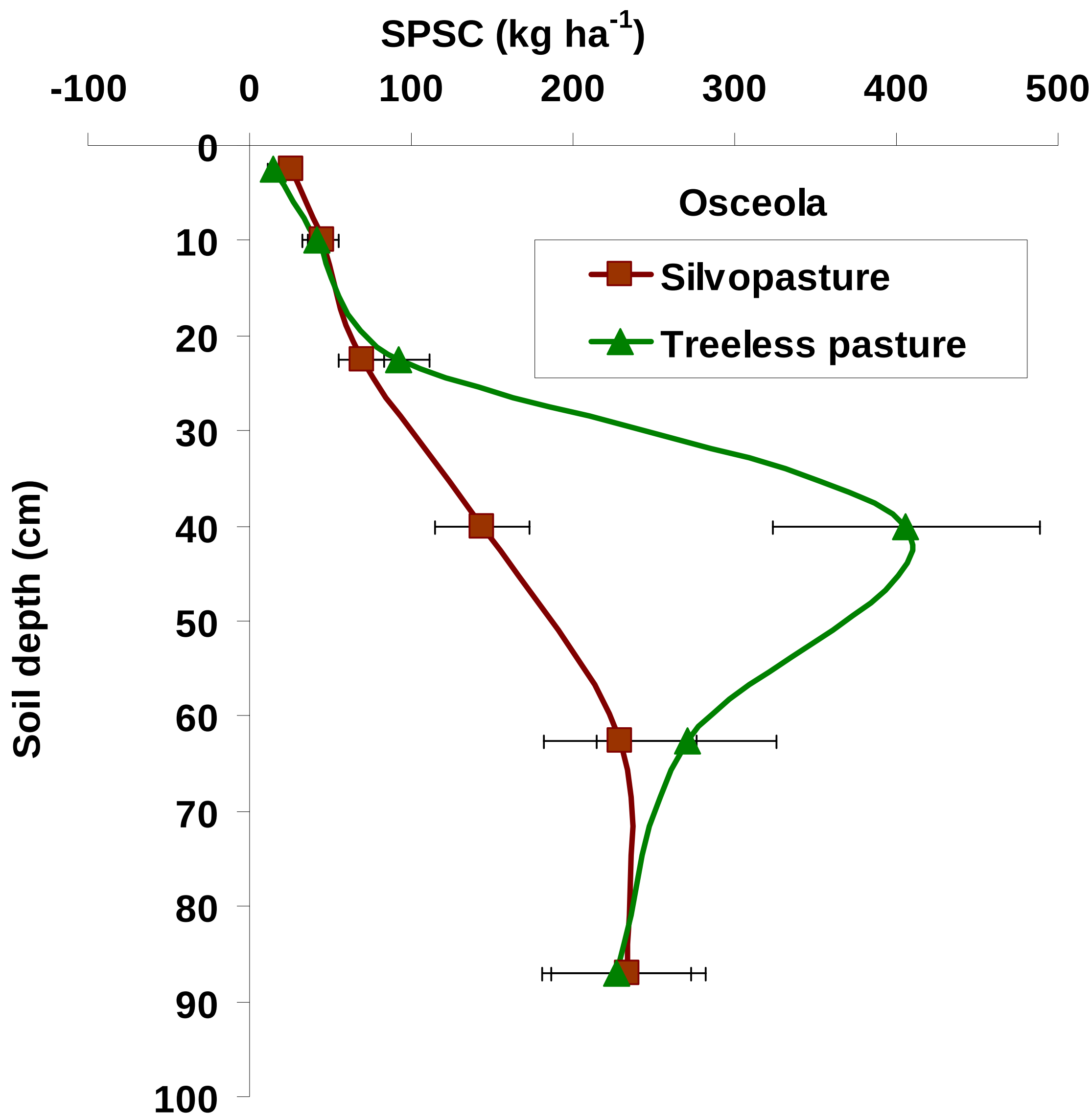

Figure 5-4. Soil P storage capacity (SPSC) by depth at the center of the alley of the silvopastures and treeless pasture sites in Osceola (error bars represent ± one standard error from the mean, n=24).

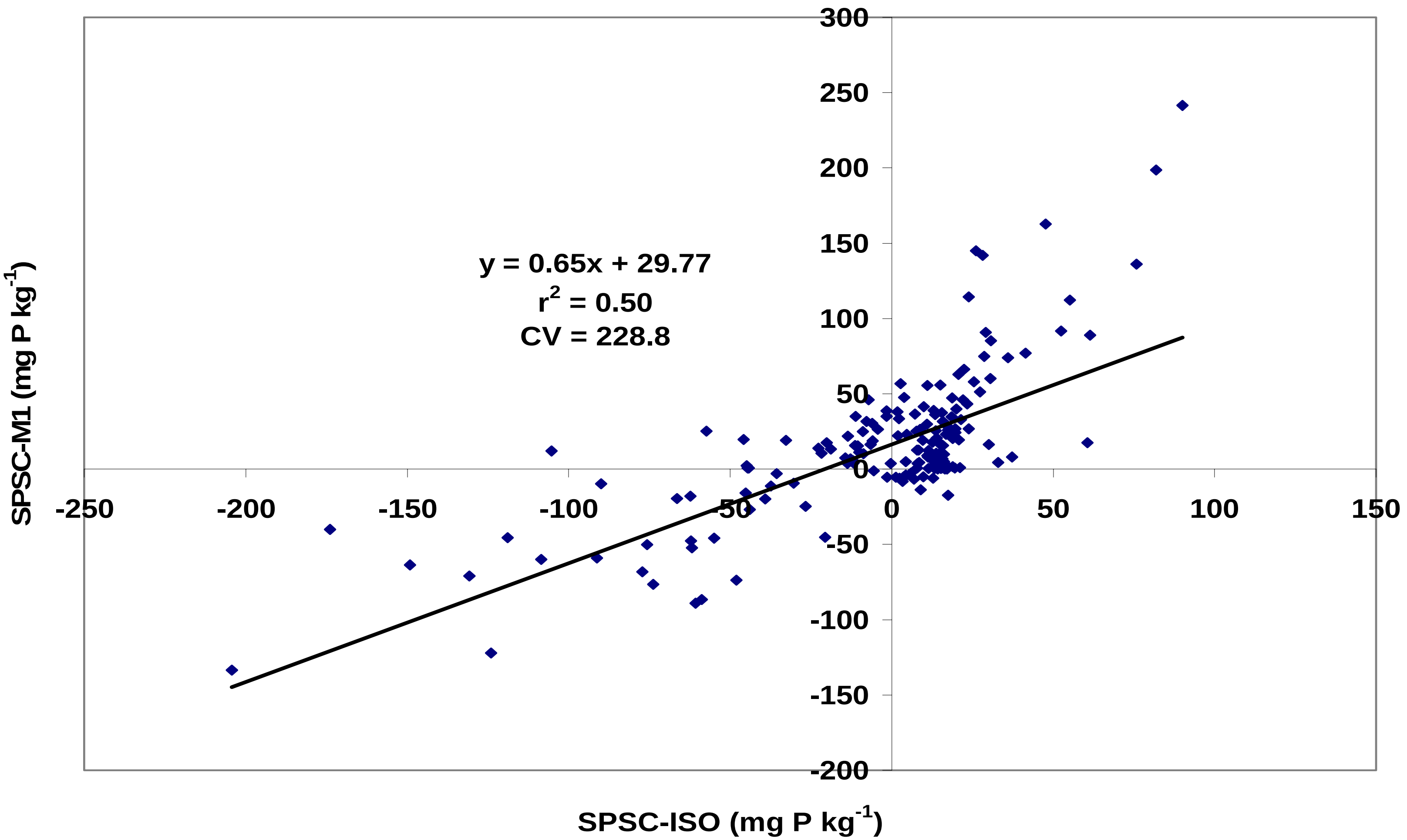

Figure 5-5. Relationship between soil P storage capacity –single point isotherm (SPSC-ISO) and soil P storage capacity-Mehlich-1 (SPSC-M1) for the surface (0 – 5 and 5 – 15 cm depths) of the study sites in Florida.

CHAPTER 6
SUMMARY AND CONCLUSIONS

Phosphorus (P) and nitrate-N loss from sandy soils that predominates pasturelands in Florida is a major cause of nutrient pollution of water bodies. Our overall hypothesis is that the loss of P to surface and ground water could be reduced in the silvopastoral systems as compared to treeless pastures. Presence of trees will enhance both nutrient retrieval from deeper soil layers and also increase nutrient accumulation capacity. As a result, silvopastoral systems can reduce nutrients losses and environmental impacts associated with farm operations.

A series of studies was conducted in Osceola (28^0 9' N, 81^0 10' W), Manatee (270 13' N, 82^0 8' W), Suwannee (30^0 24' N, 83^0 0' W), and Alachua (29^0 45' N, 82^0 33' W) counties in Florida, investigating the "safety net" function of slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) silvopastoral systems on heavily manured and porous pastureland soils in Florida. The goal of these studies were to evaluate if the presence of trees on pastureland would decrease soil P levels and thereby increase the capacity of the soil to store additional P. Soil nitrate-nitrogen (NO_3-N and NH_4-N) and phosphorus (P) concentrations were measured in soil profiles of the two pasture production systems (silvopasture vs. treeless pasture) at six depths: 0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75 and 75 – 100 cm. The remaining soil P storage capacity, which represents the maximum amount of P that can be safely applied to a soil before it becomes an environmental concern, was then estimated.

Soil characterization studies (Chapter 3) confirmed the coarse texture and acidic conditions of the soils at the study sites, typical of the southeastern USA. Ultisols had higher soil Al and Fe concentrations in the top 30 cm of depth, compared to Spodosols and they also had higher clay content in the deeper 75 – 100 cm soil layer.

The safety-net-validation study (Chapter 4) showed that silvopastures sites contained less P in the soil profile than treeless pastures suggesting a "tree effect" on nutrient retention in soils. Silvopasture would possibly increase the nutrient stock in the plant system following enhanced total nutrient uptake by trees and associated forage species, compared to the shallow-rooted forage species. The amount of P that could be transported to surface water could thus be reduced in the silvopstoral system. Although a similar trend was observed in the case on nitrogen, the differences between the two systems were less striking, possibly because of the difficulties in capturing the highly dynamic soil nitrogen dynamics at a single point in time.

Based on estimates of "the remaining soil P storage capacity" of the soils (Chapter 5) it is concluded that that the presence of trees appears to enhance remaining P storage capacity and thus may reduce potential P losses, particularly in Ultisols. This, in turn, would suggest that silvopastoral systems would provide a greater environmental service in regard to water quality protection compared to treeless pastures under similar ecological settings. The single point isotherm method provided a better estimate of the remaining Soil P Storage Capacity compared to the Mehlich-1 method.

These studies indicate that silvopastoral systems offer a means of managing nutrient inputs for enhanced nutrient use efficiency and surface and quality groundwater preservation. These results are, however, of preliminary nature. Several unknown factors remain to be investigated in more detail. For example, the relative impact of these agroforestry systems may vary depending on a number of site-specific factors such as tree and crop species, system design and management practices. Actual absorption and retention capacity of both silvopastoral and treeless pasture systems should be compared using labeled isotope and other approaches. Similarly, the effect of relatively lower soil nutrient levels in silvopastoral system as compared to treeless pasture system on N and P leaching and run-off losses should be demonstrated using run-off samplers and sampling wells. Establishing long-term on-farm runoff plots and on-site wells for monitoring nutrient dynamics in this plant-soil-water continuum will help confirm the effectiveness of these agroforestry systems in reducing nutrient loss. Overall, the findings from this study offer a preliminary, yet significant contribution to our understanding of the nutrient-capture capacity of tree-based systems and their potential use in the remediation of P-impacted sites in Florida. These results provide a conceptual framework for additional research that may facilitate enhanced utilization of slash pine + bahiagrass silvopastural systems to provide environmental and ecological services. Such systems may afford non-industrial private landowners and livestock operators with a viable alternative for current land uses.

APPENDIX
REGRESSION ANALYSIS

1. Regression analysis of water soluble P and phosphorous saturation ratio for the top 0-15 cm depth.

Parameter*	Estimate	Error	t value	P
Intercept	0.74	0.18	4.08	0.0001
linear	29.21	1.31	22.35	0.0001

Parameter	Estimate	Error	t value	P
Intercept	0.21	0.20	1.03	0.31
linear	43.86	2.90	15.11	0.0001
quadratic	-41.30	7.33	-5.63	0.0001

Parameter	Estimate	Error	t value	P
Intercept	0.43	0.22	1.97	0.0495
linear	31.54	5.71	5.53	0.0001
quadratic	35.19	31.41	1.12	0.2628
cubic	-102.98	41.12	-2.50	0.0124

Parameter	Estimate	Error	t value	P
Intercept	0.28	0.24	1.17	0.2438
linear	45.19	9.7	4.66	0.0001
quadratic	-106.54	87.35	-1.22	0.2228
cubic	334.91	255.19	1.31	0.1896
quartic	-395.70	227.60	-1.74	0.0824

*The dependent and the independent variables are respectively water soluble P and phosphorus saturation ratio.

2. R-squared selection method for soluble P and phosphorous saturation ratio for the top 0-15 cm depth.

Number in model	r-squared	Variables in the model
1	0.31	Linear
2	0.32	Linear quadratic
3	0.33	Linear quadratic cubic
1	0.26	Exponential
1	0.21	Logarithmic
1	0.02	Inverse

3. Regression analysis of soil P storage capacity-Mehlich-1 and soil P storage capacity-single point isotherm

*Parameter	Estimate	Error	t value	P
Intercept	29.77	2.74	10.86	0.0001
linear	0.65	0.05	12.83	0.0001

Parameter	Estimate	Error	t value	P
Intercept	30.54	2.61	11.72	0.0001
linear	1.01	0.09	11.17	0.0001
quadratic	0.0025	0.00053	4.71	0.0001

Parameter	Estimate	Error	t value	P
Intercept	27.32	2.60	10.50	0.0001
linear	1.18	0.095	12.41	0.0001
quadratic	0.008	0.0014	5.83	0.0001
cubic	0.000022	0.000005	4.30	0.0001

Parameter	Estimate	Error	t value	P
Intercept	25.91	2.76	9.40	0.0001
linear	1.10	0.10	10.28	0.0001
quadratic	0.00097	0.0018	5.45	0.0001
cubic	0.000051	0.00002	2.56	0.0113
quartic	0.000000008	0.000000006	1.51	0.1317

*The dependent and the independent variables are respectively soil P storage capacity-Mehlich-1 and soil P storage capacity-single point isotherm

4. R-squared selection method for soil P storage capacity-Mehlich-1 and soil P storage capacity-single point isotherm.

Number in model	r-squared	Variables in the model
1	0.47	Linear
2	0.52	Linear quadratic
3	0.56	Linear quadratic cubic
1	0.1231	Exponential

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BIOGRAPHICAL SKETCH

Gérard-Alain Michel, the third of three siblings, was born December 12, 1969, in Port-au-Prince, Haiti. Alain is a husband and a father of a 6 year-old boy named Alain-Christian Michel. In July 1996, he received his BS in agronomy from the School of Agricultural and Environmental Sciences of Quisqueya University, Port-au-Prince, Haiti. After working for 2 years in extension at Quisqueya University in a Kellogg-funded project of rural development called UNIR/UniQ, he won a Fulbright Scholarship to study in the United States, where he received, in 2000, his M.Sc. in forest resources management at the School of Environmental Science and Forestry of the State University of New York, Syracuse, New York. Back in Haiti, he was appointed faculty member at the School of Agricultural and Environmental Sciences of Quisqueya University, where he taught two courses. Less than two years later, in spring 2002, he obtained a research assistantship to start a PhD program in Agroforestry at the School of Forest Resources and Conservation of the University of Florida under the supervision of Dr. P.K.R. Nair.