ENVIRONMENTAL QUALITY IMPROVEMENT OF AGRICULTURAL LANDS THROUGH SILVOPASTURE IN SOUTHEASTERN UNITED STATES

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ABSTRACT: We hypothesized that, because of the ability of trees to sequester carbon (C) in the deep soil profile and remove excess nutrients from soils, the silvopastoral agroforestry system could enhance the environmental quality of the agricultural lands. To test this hypothesis, two sets of experiments were conducted in two soil orders in Florida, Spodosols and Ultisols, with two major objectives: i) determining the soil C accumulation and tracing the plant sources of C in soil fractions, and ii) quantifying water soluble phosphorus (WSP) and estimating the Soil P Storage Capacity (SPSC). Total C in both soil orders was greater under silvopasture than in treeless pastures, particularly at lower depths. Stable-isotope signature analysis suggested that C_3 plants (in this case, slash pine, *Pinus elliotii*) contributed to a more stable C fraction than C_4 plants (in this case, bahiagrass, *Paspalum notatum*) at soil depths up to 1 m. WSP was consistently higher in treeless pastures, while the remaining SPSC was lower in this land-use system, suggesting the greater likelihood of P moving out of the soil under treeless pasture than in silvopasture. Thus, the presence of trees in pastures contributed to more stable C within the soil profiles, lower WSP, and greater SPSC, indicating more environmental benefits provided by silvopastoral systems as compared to treeless pastures under similar ecological settings.

Key words: carbon sequestration, nutrients, soil P storage capacity, treeless pasture

MELHORIA DA QUALIDADE AMBIENTAL DE TERRAS AGRICULTÁVEIS POR MEIO DA SILVOPASTAGEM NO SUDESTE DOS ESTADOS UNIDOS

RESUMO: Nossa hipótese é de que devido à habilidade das árvores seqüestrarem carbono (C) no perfil profundo do solo e remover o excesso de nutrientes dos solos, o sistema de silvopastagem agroflorestal poderia melhorar a qualidade ambiental de terras agricultáveis. Para testar esta hipótese, dois grupos de experimentos foram conduzidos em duas ordens de solos na Florida, Espodossolos e Ultissolos, com dois objetivos principais: i) determinar a acumulação de C do solo e investigar as fontes de C para as plantas nas frações dos solos, e ii) quantificar o fósforo solúvel em água (FSA) e estimar a capacidade de armazenamento de fósforo no solo (CAFS). O C total em ambos os solos foi maior sob o sistema de silvopastagem do que sob pastagens com menos árvores, particularmente nas profundidades mais baixas. A análise por assinatura de isótopo estável sugeriu que as plantas C_3 (neste caso, slash pine, *Pinis elliotti*) contribuíram mais para a fração estável do carbono do que plantas C_4 (neste caso, bahiagrass, *Paspalum notatum*) nas profundidades dos solos acima de 1 m. O FSA foi consistentemente maior em pastagens com poucas árvores, enquanto que a CAFS foi mais baixa neste sistema, sugerindo a grande probabilidade do fósforo ser mais facilmente movido do solo sob pastagens com poucas árvores do que nos sob silvopastagem. Deste modo, a presença de árvores em pastagens contribuiu para C mais estável nos perfis dos solos e o mais baixo FSA e a maior CAFS indicaram os grandes benefícios ambientais fornecidos pelos sistemas de silvopastagem comparados com as pastagens com poucas árvores em condições ecológicas similares.

Palavras-chave: sequestro de carbono, nutrientes, capacidade de armazenamento de P no solo, pastagens sem árvores

INTRODUCTION

Silvopasture - the integration of trees with forage and livestock (Nair, 1993; Garrett et al., 2000) - is one of the most prevalent forms of agroforestry found in the United States and Canada, with the largest blocks of grazed forests occurring in the southern and southeastern United States (Clason & Sharrow, 2000). In Florida, USA, ranching that covers about 2.4 million ha and involves 1.8 million cattle is an important agricultural enterprise with more than $300 million turnover (USDA-NASS, 2002). Cattle ranches and croplands are an environmental threat to water quality due to nutrient loading and sediment toxicity and are impacting the natural systems in the Everglades, and interfering with their restoration efforts (Nair & Graetz, 2002; Pant & Reddy, 2003). The land-use and land-cover changes associated with the removal and fragmentation of natural vegetation for establishment of agricultural enterprises and real-estate development are responsible, to a large extent, for the decline in biodiversity, invasion of exotic species, and alterations to nutrient-, energy-, and water flows that often result in soil erosion, deterioration of water quality, and environmental pollution (Solecki, 2001; Hawkins & Selman, 2002).

Research that led to the development of the concept of silvopasture in southeastern USA can be traced back to the agronomic evaluation trials of warm season grasses and legumes under natural stands of longleaf pine (*Pinus palustris*) and slash pine (*Pinus elliottii*) that started in the 1940s (Burton & Matthews, 1949). Several studies conducted since then have produced results influencing the practice of silvopasture (Halls et al., 1957; Lewis et al., 1983; Lewis & Pearson, 1987; Pearson & Rollins, 1987; Clason, 1995; Zinkhan & Mercer, 1997), especially in the configuration of trees and the type of forage grass used by landowners. Recent work in silvopastoral systems suggests that compared with treeless pastures, silvopasture might have a greater potential to sequester carbon (C) (Haile et al., 2006), and also to remove excess nutrients (Nair et al., 2007) particularly from the deeper horizons of sandy soils which could result in environmental improvement of agricultural lands.

Integration of trees into a pasture system presents a unique opportunity to use the stable isotope methodology to study soil organic C dynamics following the shift in vegetation structure. The plant community in a silvopasture system comprises C_3 plants (pine trees; $\delta^{13}C \approx -29.5$ ‰) and C_4 plants dominated by grass species such as bahiagrass (*Paspalum notatum*; $\delta^{13}C \approx -13.3$‰). Differences in isotope ratio can, therefore, be used to quantify the contribution of plants following the two photosynthetic pathways to soil organic C (Balesdent & Mariotti, 1996).

The overall objective of this research was to evaluate the potential of silvopastoral systems to improve environmental quality of agricultural lands through carbon sequestration and nutrient removal as compared to the conventional land-use system of treeless pasture at two sites in Florida, USA located on different soil orders (Figure 1). Specific objectives were to: i) determine the total C in the soil profiles of slash pine-based silvopasture and adjacent treeless pasture systems, quantify the C fractions stored within soil profiles of the land-use systems, and trace the plant sources of C fractions using stable isotope signatures at both sites; and ii) quantify water soluble P (WSP) in surface and subsurface soil horizons of silvopastoral and treeless pasture systems and estimate the remaining soil P storage capacity (SPSC) of the study sites.

MATERIAL AND METHODS

Study Area: Two sites were selected, one on an Ultisol and the other on a Spodosol, each with a silvopasture system consisting of slash pine + bahiagrass, and an adjacent treeless pasture of bahiagrass.

The Ultisol site is located at the Sheriff's Boys Ranch, Live Oak, Suwannee County in Florida, USA (30°24' N, 83°0'W) (Figure 1). Both the silvopasture and the treeless pasture are on Ultisols (Blanton: loamy, siliceous, semiactive, thermic Grossarenic Paleudults). The Blanton series consists of very deep, somewhat excessive to moderately well-drained soils with an Ap horizon, followed by E and Bt horizons (USDA-NRCS, 2004). In the silvopasture, the slash pine trees were planted in single rows with a 1.5 m × 7.2 m configuration with bahiagrass in its alley. The silvopasture had never received any fertilization during its 40-year life. The bahiagrass treeless pasture was also 40 years old, but received a minimal amount of fertilization – a 19-5-19 application at 336 kg ha^{-1} in 2003 and a 224 kg ha^{-1} in 2004. Dolomite, at 4.5 t ha^{-1} has been applied every 4 years since 1978.

The Spodosol site (28°9' N, 81°10'W) is located at a private ranch in St. Cloud, Osceola County, Florida, USA (Figure 1). Both the pastures are on Spodosols (Immokalee: sandy, siliceous, hyperthermic Arenic Alaquods). The Immokalee series consists of deep and very deep, poorly drained soils with an A horizon, followed by an eluted E horizon, below which is a Bh (spodic horizon) (USDA-NRCS, 1993). The silvopasture was also planted with slash pine, but had a double row configuration 3.1 m × 1.2 m with its 12.2 m alley planted to bahiagrass. The 12-year old silvopasture was a treeless pasture for 15 years be-

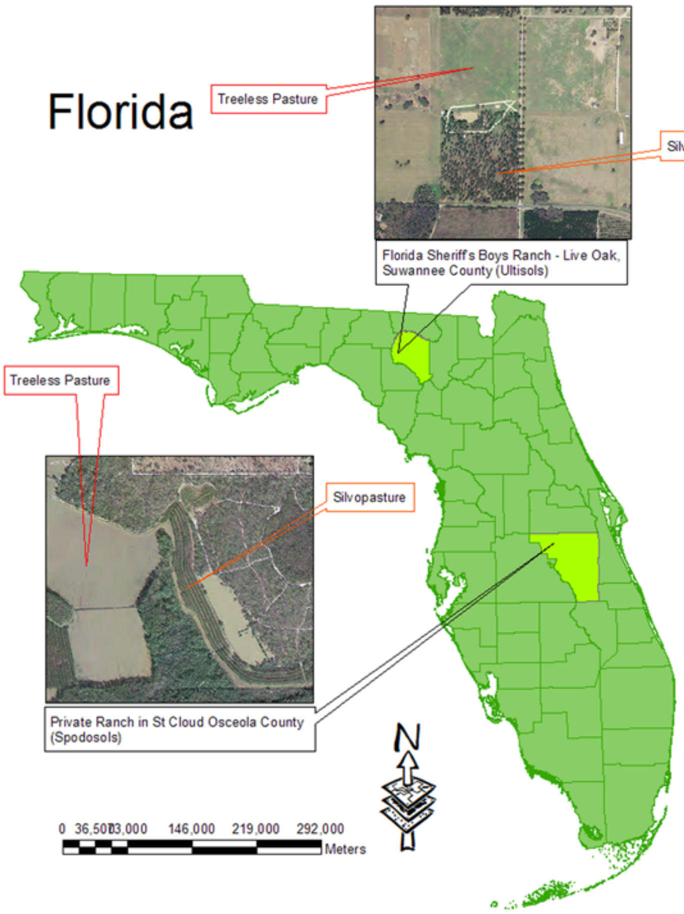

Figure 1 - Silvopasture and treeless pasture locations at the Ultisol site in Suwannee County, and the Spodosol site in Osceola County, Florida, USA.

fore the silvopasture was established, and was at that time regularly fertilized and limed. The adjacent bahiagrass treeless pasture though older (~ 45 years) had never received any fertilization.

Soil Sampling and Analyses for Carbon Studies: Soil profiles were sampled by depth (0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75, and 75 – 125 cm) at the silvopasture and at the treeless pasture. For each treatment (silvopasture and treeless pasture), 4 × 3 stratified grid sampling points were located. A composite was prepared from four of the sampling points resulting in three sets of samples per treatment for each sampling depth. Total number of soil samples for the carbon study was 72 (two sites × two treatments × three reps × six depths).

Particle Size Fractionation: Wet sieving through two sieves (250 and 53 μm) was made and three fraction size classes (2000 - 250 μm, 250 - 53 μm and <53 μm) were obtained (Elliot, 1986). The whole soil sample and fractionated samples (total number of soil samples = 72 × 4 = 288) were finely crushed to homogenize them for organic C analysis. Total organic C was determined by dry combustion on an automated FLASH EA 1112 N/C elemental analyzer and VG602 micromass spectrometer was used for C isotope ratio measurements. Note: Terrestrial plants with Calvin cycle (C_3) have δ^{13}C values of -22‰ to -33.0‰ (average -25‰), whereas plants with C_4-dicarboxylic acid cycle have δ^{13}C values of -10 ‰ to -20 ‰ (average -12‰). Percent contribution for the whole soil and fractions were calculated by the procedure of Balesdent et al. (1998).

Calculation of percent contribution by C_3 plants: Carbon isotopic ratios are expressed in δ^{13}C‰, notation which is per mil deviation of ^{13}C/ ^{12}C ratio of sample (R_{sample}) from the standard Pee Dee Belemnite (R_{PDB}), as follows: $\delta^{13}C‰= [(R_{sample/}\ R_{PDB}) – 1] \times 1000$.

The relative proportion of soil organic carbon derived from the C_4 plant (grass) vs. the C_3 plant (trees) was estimated by mass balance: % contribution by C_4 plants = $(\delta – \delta_L / \delta_G – \delta_L) \times 100$, where:
δ is the δ^{13} C of a given sample, δ_L a composite sample of the C_3 plant and δ_G is a composite sample of pasture grass tissues (C_4)

Percent contribution by C_3 plants = 100 - % contribution by C_4 plants

Soil sampling and analyses for phosphorus

Twenty-four soil profiles were sampled at successive depths (0-5, 5-15, 15-30, 30-50, 50-75 and 75-100 cm) in the silvopastures and in the treeless pastures resulting in a total of 576 soil samples (two sites × two treatments × 24 profiles × six depths). All soils were analyzed for water soluble P (WSP, 1:10 soil: water ratio) and Mehlich 1-P, Fe, Al (1:4 soil:solution ratio). The Mehlich 1 solution, also known as a double acid solution is a mixture of 0.0125 M H_2SO4 and 0.05 M HCl (Mehlich, 1953).

Calculation of the Phosphorus Saturation Ratio and the Soil Phosphorus Storage Capacity: The phosphorus saturation ratio (PSR) was computed as the molar ratio of Mehlich1-P and Mehlich1-Fe and Al (Nair et al., 2004) and soil phosphorus storage capacity (SPSC) calculated as: SPSC = (0.15-PSR) * ((Mehlich 1-Fe/55.8) + (Mehlich 1-Al/27)) * 31 (mg P kg^{-1}) (Nair & Harris, 2004). The SPSC, which provides an estimate of the amount of P that can be safely applied to the volume or mass of soil that is represented by the depth of sampling (before the soil poses an environmental P risk), was then calculated on a kg ha^{-1} basis taking into consideration a bulk density of 1500 kg m^{-3}.

RESULTS AND DISCUSSION

Soil characteristics

Soil profile characteristics of the silvopastoral and treeless pasture locations on Ultisols (Figure 1) showed little differences in sand, silt and clay composition within the sampled depths (Table 1). There were no differences in Mehlich 1-extractable Al throughout the Ultisols and minimal differences in extractable Fe concentrations. Spodosol profiles generally indicated little

Table 1 - Soil profile characteristics of the silvopasture and treeless pasture locations at the Ultisol site in Suwannee County, Florida, USA, and at the Spodosol site in Osceola County, Florida, USA.

Treatment	Depth	pH	Sand	Silt	Clay	Mehlich 1-Al	Mehlich 1-Fe
	cm		---------------- g kg^{-1} ----------------			----------- mg kg^{-1} -----------	
	Ultisol site						
Silvopasture	0-5	4.7	940	30	30	160 Ø 67	25 Ø 7
	5-15	4.9	950	30	20	253 Ø 89	28 Ø 10
	15-30	5.1	940	30	30	246 Ø 101	19 Ø 8
	30-50	5.1	940	40	20	184 Ø 84	16 Ø 5
	50-75	5.1	950	30	20	141 Ø 70	14 Ø 5
	75-100	5.0	950	30	20	123 Ø 58	13 Ø 7
Treeless pasture	0-5	6.6	940	20	40	183 Ø 74	10 Ø 9
	5-15	6.1	940	30	30	266 Ø 89	16 Ø 10
	15-30	6.0	940	40	20	259 Ø 98	14 Ø 7
	30-50	6.0	940	30	30	230 Ø 105	12 Ø 6
	50-75	6.1	940	30	30	190 Ø 102	10 Ø 5
	75-100	6.1	940	30	30	151 Ø 87	10 Ø 5
	Spodosol site						
Silvopasture	0-5	4.5	960	20	20	225 Ø 305	13 Ø 16
	5-15	4.6	960	30	10	181 Ø 356	9 Ø 6
	15-30	4.7	960	20	20	181 Ø 305	11 Ø 11
	30-50	4.6	960	30	10	298 Ø 370	5 Ø 4
	50-75	4.5	970	20	10	395 Ø 338	4 Ø 2
	75-100	4.4	960	20	20	428 Ø 277	3 Ø 1
Treeless pasture	0-5	4.4	920	40	40	132 Ø 222	27 Ø 35
	5-15	4.5	920	60	20	156 Ø 265	30 Ø 18
	15-30	4.9	920	50	30	235 Ø 401	12 Ø 12
	30-50	4.9	930	40	30	464 Ø 471	11 Ø 15
	50-75	4.8	960	20	20	428 Ø 356	8 Ø 8
	75-100	4.7	950	30	20	364 Ø 312	6 Ø 6

differences at corresponding depths for the silvopastures and treeless pastures for sand, silt and clay, and Mehlich 1-extractable Al (Table 1). Iron concentrations were generally low, but there were differences ($P < 0.05$) in their concentrations between the silvopasture and treeless pasture sites at almost all depths within the soil profiles. There were differences in pH in the soil profiles between the silvopasture and treeless pasture on the older (40 yr) Ultisol site and differences were minimal for the Spodosol site (Table 1).

Carbon sequestration

In the whole soil: The total soil organic carbon (SOC) accumulated in the surface horizons of the silvopasture plot was higher than that of treeless pasture at the Ultisol site but no difference was observed at the Spodosol site. At the lowest depth, however, the SOC accumulation was consistently greater for the silvopasture at both sites ($P < 0.01$) (Table 2). The higher SOC in the 75-125 cm layer at the silvopastoral location could be due to the effect of roots. In the whole soil of the Ultisol site, the percent contribution by trees (C_3 plant) to the SOC was significantly higher at corresponding depths in the silvopasture as compared to the treeless pasture (Table 2), except at the lowest depth. At the Spodosol site, the contribution by C_3 plants was also greater throughout the soil profile of the silvopasture and significantly higher at some of the depths (Table 2). Results suggest greater sequestration of SOC in tree-based pasture systems as compared to treeless systems, though C sequestration may also be influenced by soil orders, i.e. dependent on the composition of the soil. For instance, there is often a close relationship between the amount of clay and silt and the amount of organic C in the soil (Hassink, 1997; Albrecht et al., 2004). A spodic horizon differs from other soil materials because of the prevalence of organically-associated Al and is likely to have very high surface area for C retention.

In the soil fractions: The percent contribution to SOC by C_3 plants was greater for all the three fractions (250-2000 μm, 53-250 μm and <53 μm) throughout the soil profile at the silvopasture as compared to the treeless pasture located on Ultisols, suggesting greater C sequestration in the 40 year-old tree-based system (Figure 2). This trend was also found at the Spodosol location (Figure 2), in spite of the younger (12-year old) silvopasture establishment. At the lower depths, for both the sites and land-use systems (Figure 2), the contribution to SOC by C_3 plants was greater than 50%, except in the largest size fraction at the treeless pasture site located on Spodosols. The silt and clay fractions (the smaller-sized fractions) are more likely to reflect the historical land use, as C in these fractions would have stayed protected for a longer period of time.

Table 2 - Total soil organic carbon (SOC) accumulated and the percentage of SOC derived from C_3 plants in the whole soil sample for treeless pasture and silvopastoral locations by depth at the Ultisol site, in Suwannee County, Florida, USA, and at the Spodosol site, in Osceola County, Florida, USA.

Soil Depth	Soil Organic Carbon		Proportion of SOC derived from C_3	
	Treeless pasture	Silvopasture	Treeless pasture	Silvopasture
	Ultisol site			
cm	kg m^{-3}		%	
0-5	28.48	47.72**	29.16	76.12**
5-15	19.26	12.64	44.88	77.96**
15-30	9.73	12.33	55.92	79.66*
30-50	6.52	8.15	59.92	81.21*
50-75	6.57	16.61**	63.05	81.18*
75-125	4.40	14.84**	63.63	82.18
	Spodosol site			
0-5	85.16	79.21	16.42	54.71**
5-15	27.56	25.79	31.06	48.59*
15-30	15.10	24.07	46.55	50.30
30-50	9.83	16.08	55.46	59.96
50-75	10.67	11.29*	55.70	60.54
75-125	8.61	12.61**	52.66	59.53**

Differences between the silvopasture and the treeless pasture at a given depth for SOC or proportion of SOC derived from C_3 plants are indicated as: * ($P < 0.05$); ** ($P < 0.01$).

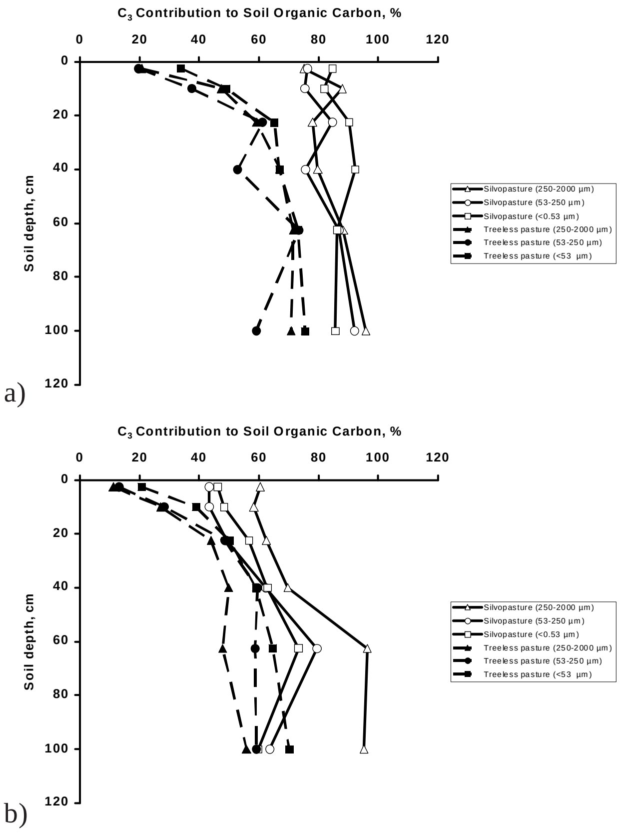

Figure 2 - Tree (C_3) contribution to soil organic carbon with depth at the silvopasture and treeless pasture locations at the Ultisol site (a) in Suwannee County, Florida, USA, and at the Spodosol site (b) in Osceola County, Florida, USA. Depth indicated is the mid-point of the sampled depth.

Phosphorus removal

At both the Ultisol and the Spodosol sites, WSP was greater in the soil profile of the treeless pasture as compared to the silvopasture (Figure 3). This observation was more pronounced at the older Ultisol site. Low WSP at the deeper horizon of the Spodosol site could be related to soil characteristics. In these poorly-drained soils, P is likely lost via subsurface flow above the P retentive Bh horizon; this phenomena was also observed by Nair et al. (2007) at another Spodosol location.

The SPSC at the Ultisol site indicates a greater potential for further P additions to be stored in the silvopasture as compared to the treeless pasture soils (Figure 4). At the surface horizons, the SPSC is negative at the treeless pasture, indicating that this soil is a P source. At the SposOsol site, there is little difference in SPSC at the surface (0-5, 5-15, and 15-30 cm) depths of the treeless and silvopasture sites. At the 30-50 cm depth (mid-point 40 cm), the SPSC increases at both the Ultisol and Spodosol sites. This depth corresponds to the occurrence of the Bh horizon in the Spodosol which has high P retention capacity. Iron and Al are responsible for the high P retention at this horizon (Nair & Graetz, 2002); the SPSC at this depth (Figure 4) may not be a reflection of the land use, but the inherent soil properties. Natural variability in soil characteristics should also be taken into account while interpreting both nutrient loss and carbon sequestration potentials from a land-use system.

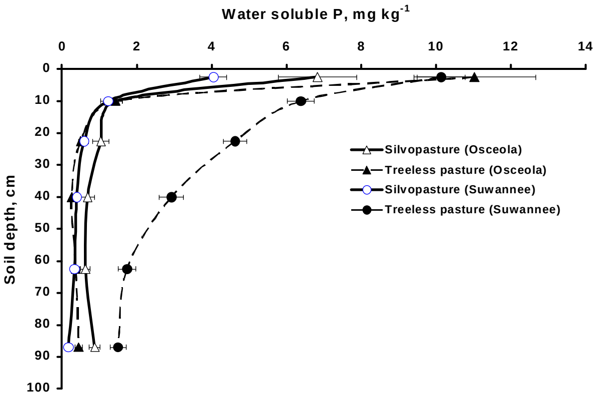

Figure 3 - Changes in water soluble P (WSP) with soil depth at the silvopasture and treeless pasture locations at the Ultisol site in Suwannee County, and the Spodosol site in Osceola County, Florida, USA. Depth indicated is the mid-point of the sampled depth.

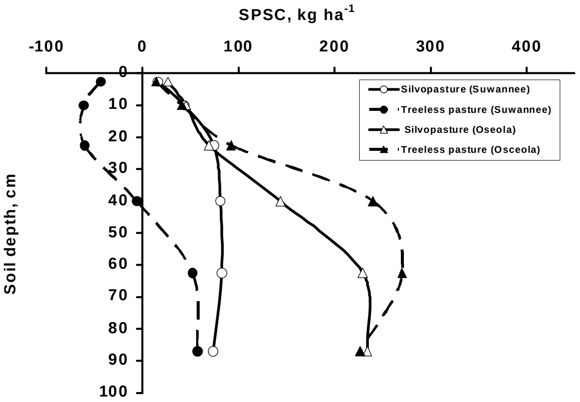

Figure 4 - Changes in soil P storage capacity (SPSC) with soil depth at the silvopasture and treeless pasture locations at the Ultisol site in Suwannee County, and the Spodosol site in Osceola County, Florida, USA. Depth indicated is the mid-point of the sampled depth.

CONCLUSIONS

The presence of trees in pastures showed higher SOC in the deeper soil profile, and the proportion of the C_3 tree contribution in the whole soil was generally higher throughout the soil profile of the silvopasture as compared to the treeless pasture at both sites. Further, the contribution to SOC by C_3 plants is greater than 50% for the smaller particle size fractions throughout the silvopastoral soil profiles; small particle size fractions are associated with the more stable C. Lower WSP in the tree-based systems and a greater capacity for the soil to retain further additions of P, particularly in Ultisols suggest that silvopastoral systems could provide greater environmental benefits as compared to treeless pastures under similar ecological settings. Thus, silvopastoral systems would likely improve environmental quality, both via increased C sequestration and nutrient removal as compared to treeless pasture systems.

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