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Use of deep-rooted tropical pastures to build-up an arable layer through improved soil properties of an Oxisol in the Eastern Plains (Llanos Orientales) of Colombia

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Abstract

It is widely believed that tropical soils (mainly Oxisols) have excellent physical characteristics such as high infiltration rates, high permeability of water, good and stable soil structure and that consequently, they can support mechanized agriculture. However in the Eastern Plains (Llanos Orientales) of Colombia, when Oxisols are subjected to tillage using disc harrow, soil physical conditions deteriorate rapidly. We report here that change in land use with deep-rooted tropical pastures can enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping. In addition, rates of water infiltration improved by 5–10-fold while rainfall acceptance capacity improved by 3–5-fold. We suggest that intensive and sustainable use of these Oxisols, could only be possible if an "arable" or "productive layer" (i.e. a layer with improved soil physical, chemical and biological properties) is constructed and maintained. One option to achieve this arable layer is through the use of introduced tropical pastures with deep-rooting abilities that can result in increased soil organic matter and associated improvements in soil physical, chemical and biological properties. One land use option that can achieve these soil improvements is agropastoralism whereby pastures and crops are grown in short-term rotations.

Keywords: Soil physical characteristics; Oxisols; Infiltration; Organic matter; Rainfall acceptance; Lower and upper limits of available water

1. Introduction

Agricultural sustainability implies that agriculture will remain the principal land use over long periods of time relative to human life-span and it is economically competitive and ecologically acceptable while the soil resource base maintains or even improves its fertility and health (Hamblin, 1991). One of the major challenges for the achievement of sustainable agriculture in the tropics, is the vulnerability of tropical soils to degradation when they are subjected to mechanization for crop production (Thomas et al., 1995; Thomas and Ayarza, 1999; Amézquita et al., 2000). It is widely believed that tropical savanna soils (mainly Oxisols) have excellent physical characteristics such as high infiltration rates, high permeability, good and stable soil structure and therefore can support mechanized agriculture (Sanchez and Salinas, 1981). However, recent work indicated that Colombian savanna soils (Oxisols of Altillanura), have serious physical, chemical and biological constraints for crop and pasture production (Amézquita et al., 1998a). Physically

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the fertile layer can be shallow with high bulk densities together with weak structure. Tillage (disc harrowing) practices currently used for seedbed preparation could result in surface sealing and low rainfall acceptance capacity (Amézquita et al., 2000). Chemically the soils have low pH values, high levels of exchangeable Al^{3+}, low P availability, low base (Ca, Mg and K) saturation and low amounts of organic matter. Also, biologically they show constraints typical of soils with low organic matter such as lower rates of mineralization (Thomas et al., 1995; Lopes et al., 1999).

Physical, chemical and biological conditions of these soils need to be improved in order to increase their productivity. Usually this improvement can be achieved by land preparation and by application of lime and fertilizer. However, this effect lasts only for a short time and after 4–7 years, farmers abandon the degraded land as it is no longer productive and often migrate to other areas. To avoid the continued degradation of these soils and to achieve sustained production, we propose that the construction of an "arable layer", a top layer with improved soil properties, is required (Amézquita et al., 2000).

It has been demonstrated that soil physical conditions are usually best under permanent grassland (or forest) and as soil is cultivated, these conditions deteriorate at a rate dependent of climate, soil texture and management (Lal, 1993; White, 1997). Amézquita et al. (1998a), have found significant negative effects of continued cropping on the physical properties of soils in the Llanos. The study by Preciado (1997) from the Casanare region of the Llanos showed that total porosity and macroporosity decrease markedly after 5–7 years of monocropping. Boonman (1997) mentioned similar trends for soils of African savannas.

Ploughing and cultivating new land is usually accompanied by a decline in soil organic matter. When land is ploughed, disruption of peds exposes previously inaccessible organic matter to attack by microorganisms and populations of soil structure-stabilizing fungi and earthworms decrease markedly (White, 1997). Introduced pastures can markedly reverse these trends through improvements in soil aggregation (Drury et al., 1991; Gijsman and Thomas, 1995; Franzluebbers et al., 2000).

The relatively weak structure of savanna soils of Colombia (Oxisols) and their susceptibility to sealing, compaction, and erosion when subjected to tillage can result in negative effects on sustainable productivity of crop-livestock systems (Amézquita, 1998). To overcome these physical constraints, tillage practices should be developed that are based on the concept of development of an "arable layer". The "arable layer" is a surface layer (0–15, 0–25, 0–30 cm depth), with improved soil physical, chemical and biological properties. This is essential for developing a soil that is capable to support sustainable agriculture (Amézquita et al., 2000).

The "arable layer" concept proposed, is based on the combination of: (1) tillage practices to overcome soil physical constraints (high bulk density, surface sealing, low infiltration rates, poor root penetration, etc.); (2) use of chemical amendments (lime and fertilizers) to enhance soil fertility; and (3) use of soil and crop management practices to increase rooting, to promote biostructure, and to avoid repacking of soil after tillage, thus, improving the biological condition of the soil. This concept relies on the use of deep-rooted and acid-soil-adapted tropical pastures to improve and maintain soil physical conditions via vertical tillage (chisel).

The purpose of this study was to evaluate the influence of deep-rooted tropical pastures in comparison with other land uses such as monocropping of upland rice and native savanna pastures on the build-up of an arable layer through improved soil properties.

2. Materials and methods

2.1. Location

The experiments were carried out at Matazul farm (4°9′4.9″N, 72°38′23″W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto Lopez, Colombia. The area has two distinct climatic seasons, a wet season from the beginning of March to December and a dry season from December to March and has an annual average temperature of 26.2 °C. The area has mean annual rainfall of 2719 mm, potential evapotranspiration of 1623 mm and relative humidity of 81% (data from the nearby Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia). The soil has low fertility and the availability of P in the soil is low because of the soil's high P fixation capacity (Phiri et al., 2001).

2.2. Treatments

To evaluate the impact of deep-rooted pastures on soil physical characteristics, we used the following treatments from long-term experiments.

(a) Aggregate size distribution and aggregate stability aspects were studied in an experiment where disturbed and undisturbed introduced pasture systems were compared with rice monocropping on two sites of contrasting soil texture (Matazul: clay-loam; Primavera: sandy-loam). Native savanna (undisturbed) system was used as a control. Disturbed pasture received two harrow passes for every 2 years to reduce surface sealing and compaction.
(b) Infiltration rates were measured in an experiment aimed to improve top-soil conditions (cultural profile) using different intensities (1, 2 or 3) of chisel passes (vertical tillage) or different agropastoral treatments (pasture alone, pasture + legume and legumes alone) that were planted after two passes of chisel.
(c) Measurements on volume and chemical composition of gravitational water were studied in an experiment aimed to understand the processes of soil degradation due to either monocropping of rice or introduced pasture (*Brachiaria dictyoneura* cv. Llanero). Different number of harrow passes (2, 4, 8) were applied every year for a period of 2 years for each treatment.
(d) Root biomass and root volume of *Brachiaria decumbens* were determined in two contrasting textural soils: sandy- and clay-loam, under two pasture conditions: productive and degraded (less productive), to compare root growth under these two conditions.

2.3. Evaluated parameters

2.3.1. Aggregate size distribution and aggregate stability

Ten volumetric soil samples were taken in cylinders (120 mm diameter by 25 mm high) and used for dry aggregate size distribution determinations from each of the following treatments: disturbed pasture, undisturbed pasture, monocrop and native savanna. Disturbed pastures means that two harrowing passes were made every 2 years to loosen the soil to improve pasture productivity. By the time of the evaluation, the experimental plots had 8 years of establishment. In each of the 10 samples taken from each treatment, a test for dry aggregate size distribution (Kemper and Rosenau, 1986; Amézquita et al., 1998b) was made using the total volume of soil collected in the cylinders. Sieves of the following openings were used: >6, 6–4, 4–2, 2–1, 1–0.5 mm, which were fitted to a shaker for 5 min.

Aggregate stability was determined also using 10 samples (50 g of soil) for each treatment with a Yoder apparatus (Angers and Mehuys, 1993). A set of sieves with openings of: 2, 2–1, 1–0.5, 0.5–0.25, 0.25–0.125 and <0.125 mm was used. The amount of sand found in each sieve was discounted from the total weight.

2.3.2. Infiltration rate

A double ring devise was used to determine infiltration rates (Bower, 1986). Five tests for each treatment were made. Internal cylinder was inserted into the soil to 5–7 cm soil depth. External cylinder was inserted to 3–5 cm. Water was poured first to the external cylinder to reach a height of about 3 cm within the cylinder and then to the internal cylinder to reach a height of 6 cm from the soil surface. The amount of water entering into the soil was measured at different time intervals during a testing period of 2–3 h, until a quasi equilibrium of amount of water entering in function of time was reached.

2.3.3. Collection of gravitational water

It is not common to collect and measure the amount and elemental composition of free water (drainage water) from the precipitation that moves down in a soil profile at different depths. In this study we determined the influence of pastures or monocropping of upland rice on the amount of gravitational water and its elemental composition at different soil depths. A pit of 1.8 m length × 0.7 m wide × 0.5 m depth m was dug in each treatment. Funnels filled with clean fine and very fine sand, were wetted to field capacity and then buried in the soil profile at different depths: 3, 5, 10, 15 and 30 cm to collect the gravitational water that passes through each depth, during part of the rainy season. Measurements of the amount of water and elemental composition, were made at different times. During the period of measurements, the pits were protected around and covered with a sheet of zinc to avoid any other water entering into the pit. This methodology assumes that there is a vertical piston like water movement. The accepted rain was assumed to move through the soil profile and reach the funnels that were buried at different depths. Wet sand present in the funnels favors pore continuity for the drainage process.

2.3.4. Root distribution

Root sampling was carried out using a trench profile method (Schuster, 1964). Three sampling points were randomly located within each treatment of degraded or productive pasture of *Brachiaria decumbens*. A trench of 60 cm wide, 50 cm deep and 60 cm long was dug to determine root penetration and root distribution. Root samples were excavated from the wall of each trench, total three samples from each treatment. The nail-boards were made of a 2 cm thick plywood board (50 cm wide and 40 cm long). Twelve centimeters long nails were inserted at 10 cm intervals (10 cm × 10 cm) through the back of the board and protruded into the frame 10 cm.

Root samples were excavated by pressing the nail-boards into the trench wall and slicing the enclosed soil monolith from the trench wall with a steel blade. The samples were soaked in water for at least 2 h after which the soil was removed from the roots with a fine spray of water. The root samples were photographed. Root volume was determined with a measuring jar filled with water by registering the increase in volume. Root biomass (dry weight) was recorded after oven drying for 2 days at 65 °C.

3. Results

3.1. Aggregate size distribution and stability

The effect of different management systems on the aggregate size distribution is shown in Table 1. At Matazul Farm, the percentage of aggregates >6, 6–4 and 4–2 mm decreased in intervened systems compared with the native savanna, while those between 2–1, 1–0.125 and <0.125 mm increased. This was noted particularly under monocropped rice. At La Primavera Farm, monocropping with rice resuted in a lower percentage of 4–2 mm and higher percentage of 2–1 and 1.0–0.125 mm aggregates. In contrast, the undisturbed pasture had a positive effect on soil aggregation, with the highest (non-significant) percentage of aggregates larger than 2 mm.

The results on aggregate stability are presented in Table 2. Aggregate stability values at Matazul Farm were greater for native savanna than for intervened systems. The percentage of stable aggregates larger than 2 mm was significantly greater in relation to other treatments. At La Primavera Farm, undisturbed pasture and native savanna both had a higher percentage of aggregates larger than 2 mm diameter.

Table 1
Aggregate size distribution (%) as influenced by soil management system in savanna soils of Colombia

Treatment	Percentage of aggregates of size (mm)[a]					
	>6	6–4	4–2	2–1	1–0.125	<0.125
Matazul Farm						
Undisturbed pasture	14 b	11 b	16 a	15 b	32 b	12 ab
Disturbed pasture	21 a	11 b	15 ab	15 b	27 c	11 b
Rice monocropping	7 c	7 c	13 b	17 a	44 a	13 a
Native savanna	22 a	14 a	16 a	11 c	24 c	10 b
La Primavera Farm						
Undisturbed pasture	14 a	15 a	26 a	17 b	22 b	5 b
Disturbed pasture	6 b	7 c	17 ab	22 a	37 a	11 a
Rice monocropping	13 a	12 b	15 b	18 b	31 a	10 a
Native savanna	11 a	11 b	26 a	18 b	24 b	9 ab

[a] Values within an aggregate size class and farm followed by the same letter are not significantly different at $P < 0.05$.

Table 2
Percentage of stable aggregates under different management systems on a Colombian savanna Oxisol

Treatment	Percentage of stable aggregates of size (mm)[a]					
	>2	2–1	1–0.5	0.5–0.25	0.25–0.125	<0.125
Matazul Farm						
Undisturbed pasture	75 c	7.2 a	4.0 a	1.6 a	1.6 a	10.0 ab
Disturbed pasture	79 bc	4.5 b	2.7 b	1.2 b	0.9 ab	11.4 a
Rice monocropping	84 b	3.6 b	2.6 b	1.2 b	0.9 ab	7.8 ab
Native savanna	93 a	1.2 c	0.6 c	0.3 c	0.3 b	4.2 b
La Primavera Farm						
Undisturbed pasture	94 a	1.0 c	0.5 c	0.5 b	0.2 b	3.7 b
Disturbed pasture	78 c	7.6 a	3.7 a	1.3 a	1.2 a	8.7 a
Rice monocropping	84 b	4.4 b	2.3 b	0.8 ab	1.0 a	7.8 a
Native savanna	93 a	1.7 c	0.6 c	0.3 b	0.2 b	4.4 b

[a] Values followed by the same letter are not significantly different at $P < 0.05$.

3.2. Infiltration rates

Infiltration rates, determined under different management system treatments in an experiment aimed to create an arable layer, are shown in Table 3. In relation to native savanna the treatments that included introduced pastures showed higher and more stable rates. Particularly higher rates of infiltration were found under *A. gayanus* pasture.

Table 3
Rate of water infiltration ($cm\,h^{-1}$) as influenced by different treatments in the experiment on building an arable layer (Matazul Farm)

Treatment	Infiltration rate ($cm\,h^{-1}$)	
	1998	1999
Rice–soybean rotation		
(1) Chisel pass	2.0 c	5.5 bc
(2) Chisel passes	1.6 c	7.4 bc
(3) Chisel passes	2.2 c	7.5 bc
Rice + pastures		
(a) Early incorporation of residues		
A. gayanus (Ag)	17.0 a	15.0 a
Ag + legumes (Kudzu + *D. ovalifolium*)	8.8 abc	5.6 bc
Legumes (Kudzu + *D. ovalifolium*)	9.7 abc	6.8 bc
(b) Late incorporation of residues		
A. gayanus (Ag)	8.5 abc	9.4 b
Ag + legumes (Kudzu + *D. ovalifolium*)	6.5 bc	5.2 bc
Legumes (Kudzu + *D. ovalifolium*)	14.2 ab	3.1 c
Native savanna (control)	1.7 c	3.7 bc
Significance level	0.07	0.006

Values followed by the same letter are not significantly different at $P < 0.05$.

3.3. Gravitational water

The amount of gravitational water draining at different soil depths as a function of soil management system is shown in Table 4. Little water was collected in the top layers of soil of savanna while greater amounts were collected at 15 cm soil depth. The treatment sown to upland rice with eight harrow passes, did not allow the movement of free water through the soil. With 16 harrow passes more water was able to enter into the soil especially in the top two layers.

Under introduced pastures, the amount of free water entering and moving through the soil profile was extremely high ($480\,cm^3$ versus $0\,cm^3$ with eight harrow passes and $490\,cm^3$ versus $100\,cm^3$ with 16 harrow passes) in comparison with upland rice.

The chemical composition of the water collected at different soil depths under upland rice and pastures is shown in Table 5. Higher amounts of nutrients, especially at the first two depths were found under rice.

3.4. Root distribution

Examination of soil monoliths collected through profile wall technique showed marked differences in root penetration and root distribution between a degraded pasture and a productive pasture of *Brachiaria decumbens* (Fig. 1). Differences in root biomass and

Table 4
Gravitational water collected (ml) at different soil depths for different systems of soil management (Matazul Farm)

Depth (cm)	Amount of water collected (ml)				
	Native savanna	Rice		Pasture	
		8 harrow passes	16 harrow passes	8 harrow passes	16 harrow passes
3	3	0	100	480	490
5	2	0	136	480	490
10	4	1	0	480	447
15	490	2	0	440	132
20	1	0	0	40	78
30	0	3	0	0	460

Table 5
Elemental composition of gravitational water collected at different depths and management systems (Matazul Farm)

Crop	Depth (cm)	N ($mg\,l^{-1}$)	K ($mg\,l^{-1}$)	Ca ($mg\,l^{-1}$)	Mg ($mg\,l^{-1}$)	Al ($mg\,l^{-1}$)	Electrical conductivity ($\mu S\,cm^{-1}$)	pH
Rice	3	8.5	12.0	2.9	0.5	6.0	103.8	5.8
	5	2.8	10.4	6.0	1.0	17.5	90.0	6.0
	3	1.7	4.1	1.7	0.5	2.2	463.0	5.9
	5	2.9	0.6	1.6	0.3	1.4	29.5	6.2
Pastures	10	2.0	1.4	0.8	0.2	0.4	288.0	6.1
	15	2.0	2.6	2.8	0.4	0.6	47.5	6.6
	20	2.7	1.5	2.3	0.4	0.5	56.3	6.7
	30	4.8	3.8	3.7	1.0	1.7	79.0	6.6

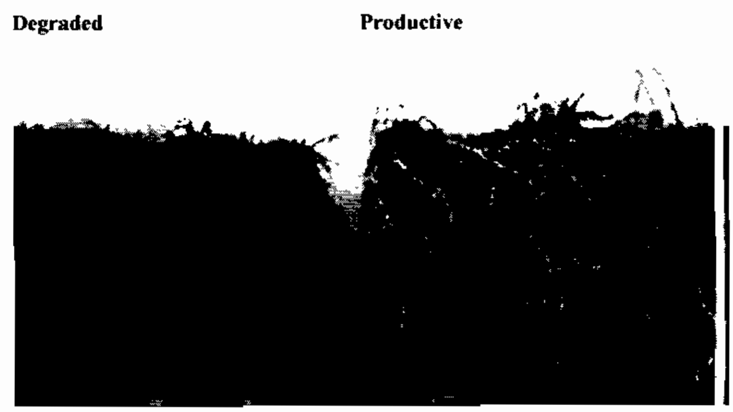

Fig. 1. Root distribution under degraded and productive *Brachiaria decumbens* pasture.

root volume at different soil depths, as influenced by soil texture (clay-loam and sandy-loam) are shown in Table 6. Clearly the productive pasture showed greater abundance and distribution of root systems than the degraded one.

4. Discussion

Good soil management should aim to create optimum physical conditions for plant growth (White, 1997). These include: (a) adequate aeration for roots

Table 6
Root biomass (g) and root volume (cm^3) of *Brachiaria decumbens* at different soil depths as influenced by level of pasture productivity (degraded or productive) on two soil types

Soil depth (cm)	Sandy-loam			Clay-loam		
	Degraded	Productive	$LSD_{0.05}$	Degraded	Productive	$LSD_{0.05}$
Root biomass (g)						
0–15	0.7	1.3	0.64	1.0	1.7	NS
15–25	0.2	0.2	NS	0.3	0.3	NS
25–40	0.1	0.3	0.08	0.2	0.2	NS
Root volume (cm^3)						
0–5	6.5	9.7	NS	8.5	15.7	5.6
15–25	2.2	2.7	NS	2.7	2.6	NS
25–40	1.2	2.7	0.8	2.1	2.1	NS

and microorganisms; (b) adequate available water; (c) easy root penetration; (d) rapid and uniform seed germination; and (e) resistance of the soil to slaking, surface sealing and accelerated erosion. Results from this study indicate that change in land use to deep-rooted tropical pasture can enhance soil quality by improving the size distribution of stable aggregates when compared with soils under continuous upland rice monocropping. The greater percentage of stable aggregates with introduced pastures compared with monocropping indicates that any kind of soil disturbance negatively affects aggregate stability, possibly through its influence on soil organic matter (Hamblin, 1985; Lal, 1993) or some of its components (Caron et al., 1992). Compared with native savanna, introduced pastures also showed higher and more stable rates of water infiltration, particularly with *A. gayanus* pasture. These results reconfirm the benefits of introduced pastures in improving soil quality (CIAT, 1998; Gijsman and Thomas, 1996).

The improvement of the structural condition of soils by pastures, when they are used for grazing, normally change to less beneficial values of porosity, infiltrability, etc. as a consequence of trampling. However, strategies to maintain a good soil structural quality can be developed with proper grazing management.

Little amount of gravitational water was collected in the top layers of soil of native savanna while greater amounts were collected at 15 cm soil depth suggesting the existence of preferential flow. This could be due to the wetting mechanisms dominant in the natural savannas. The treatment sown to upland rice with eight harrow passes, did not allow the movement of free water through the soil, probably as a result of surface sealing that impeded the entrance of water. Under 16 harrow passes more water was able to enter into the soil especially in the first two depths, showing that there was a better rainfall acceptance under this treatment. The greater amounts of gravitational water entering and moving through the soil profile of introduced pasture in comparison with monocropping of upland rice indicates that introduced pastures are a very good alternative to improve and maintain the amount of macropores (pores that permit the free movement of water). This result confirms the beneficial effects of agropastoral system for improvement of these soils (Angers, 1992). Results on the chemical composition of the gravitational water collected indicate the beneficial effects of introduced pastures both on water and nutrient redistribution in the top-soil layers. However, it is important to note that pastures were sown a year before rice.

Four aspects of the research deserve to be emphasized. First, the methodology used was appropriate as it was possible to collect drainage water and differentiate between treatments. Second, there was a very high variability in the way the water moved into the soil (preferential flow). Third, the amount of nutrients that moved from one depth to the other was a function of the total amount of water draining through soil profile. Fourth, the greater capacity of the pastures for facilitating a better movement and distribution of nutrients and water could be used for improving soil physical conditions.

5. Conclusions

This study shows that change in land use as introduced pastures can enhance soil quality by improving the size distribution of stable aggregates, water infiltration rates and rainfall acceptance capacity when compared with soils under monocropping. We suggest that the intensive and sustainable use of these soils, is only possible if an "arable" or "productive layer" is produced and maintained, i.e. a layer with little physical, chemical and biological constraints. One option to achieve this arable layer is the use of introduced pastures with deep-rooting abilities that can result in increased soil organic matter and associated improvements in soil physical and chemical properties. One land management option that can achieve these improvements is agropastoralism whereby pastures and crops are grown in short-term rotations.

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