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Roots of *Stylosanthes hamata* create macropores in the compact layer of a sandy soil

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Abstract

The paper presents results of a field experiment designed to investigate the potential use of forage legume *Stylosanthes hamata* (stylo) to ameliorate the structure of a compact layer in sandy soils of Northeast Thailand. Sandy and acidic soils that are common to Northeast Thailand have restricted agronomic potential due to inherent chemical and physical properties. A compact layer at 20–40 cm reduces root elongation for most crops, thereby restricting the quantity of nutrients and water available for the plant growth. Deep ploughing and subsoiling are costly and have not been shown to be effective in overcoming compaction since these soils are unstable and collapse after the first heavy rainfall event. A three-year study was conducted in order to evaluate the effect of continuous stylo on the porosity of the compact layer and its influence on root elongation and yield of a subsequent maize crop. Continuous stylo was grown for two years in experimental plots and compared to a currently used stylo-maize rotation. Root distribution and macropore density were measured under the two cropping systems. After 24 months of continuous stylo, roots were able to penetrate the compact layer, resulting in a significant improvement in the macroporosity of this layer. The subsequent maize crop developed a deeper and more extensive root system using macropores created after 24 months of continuous stylo when compared to the stylo-maize rotation treatment. This study demonstrates the potential role of *Stylosanthes hamata* in structural amelioration of sandy compact layers.

Introduction

Light textured soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (Panichapong, 1988). Such soils occupy a significant area of the Northeast Thailand plateau (Ragland and Boonpuckdee, 1987). The vegetation was originally dominated by climax *Dipterocarp* forests until 40 years ago, when they were extensively cleared for timber and agriculture. In their pristine state these soils are highly productive in that they support climax forest communities. However, when cleared and placed under agricultural production, they become problematic and their productivity declines rapidly (Kheoruenromne et al., 1998).

These soils are often characterised as being of a sandy texture, acidic to depth (pH_{CaCl2} around 4.0) with very low exchange properties (CEC < 2.5 $cmol_c\ kg^{-1}$) and therefore a low nutrient supplying capacity. Similarly, the physical characteristics of these soils are poor with a compact layer often developing at 20–40 cm that prevents root proliferation at depth (Bruand et al., 2004; Hartmann et al., 1999). Whilst this layer restricts root growth it does not prevent the rapid drainage of these soils and therefore does not enhance the water holding capacity as observed in other compact sandy soils (Mamman and Ohu, 1997). Therefore a plant with deep-rooting characteristics could potentially enhance the rooting characteristics of subsequent crops, thereby improving

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soil nutrient recycling and crop productivity (Salako et al. 2002).

The impacts of soil structure on root growth and proliferation is a topic that has received considerable attention over the past decade (Passioura, 1991; Stirzaker et al., 1996; Angers and Caron, 1998). It has been shown that root proliferation in the soil is closely dependent on the presence of macropores (Hatano et al., 1988; Hatano and Sakuma, 1990; Stewart et al., 1999). Various studies, using artificial impenetrable subsoils containing arrays of cylindrical holes (Dexter, 1986), artificial perforations of a compact layer (Nambiar and Sands, 1992) or artificially-made macropores that simulated vertically oriented bio-pores (Nakamoto, 1997), confirmed the importance of macroporosity in improving root proliferation below compacted layer by subsequent crops. Mechanical modification of the soil profile, through deep-ploughing or subsoiling, is able to significantly increase the porosity of soils. However, such profile modifications require significant inputs of energy that is often beyond the means of resource-poor farmers and invariably, the benefits diminish rapidly after the first heavy rains due to the inherently unstable nature of these soils (Hartmann et al., 2002). Actively growing plant root systems have the potential to ameliorate subsoils in poor physical condition by biological drilling (Cresswell and Kirkegaard, 1995). Decaying roots leave a continuous network of vertically-oriented macropores that the subsequent plants can use (Volkmar et al., 1996; Angers and Caron, 1998). It has been shown for example, that a severely compacted sandy loam soil can be ameliorated by a cover-crop through the combined effects of organic mulches and root drilling (Stirzaker and White, 1995). At the other extreme of soil texture, Pillai and McGarry (1999) have demonstrated that plant roots were able to improve the structure of a compacted vertisol (roots and wet-dry cycle actions).

Stylosanthes hamata has the ability to significantly increase the number of macropores in long-term tropical legume/pasture mixes through the process of root drilling (Bridge et al., 1983) and is therefore an ideal low-cost method for improving the quality of native pastures and legume-based cropping systems (Miller et al., 1991; Oikeh et al., 1998). In contrast, the growing of *Stylosanthes hamata* in a 3–4 month rotation with a non-legume crop has been shown to increase the nitrogen content of the soil and, therefore supply nitrogen to the subsequent crop, but had no effect in ameliorating soil structure in Northeast Thailand (Ruaysoongnern and Aitken, 1980). This may in part be attributed to the short duration of the legume component since it has been observed that the density of macropores under *Stylosanthes hamata* increases significantly only after several years of permanent pasture (Bridge et al. 1983).

A three year field study was undertaken to investigate the potential role of *Stylosanthes hamata* in ameliorating the structure of a compact layer in a typical light textured soil in Northeast Thailand. The effectiveness of stylo in enhancing the rooting depth of a subsequent maize was assessed with respect to (i) the ability of the species to penetrate a compacted layer, (ii) the creation of macropores by roots into the subsoil and (iii) the benefits to the subsequent maize crop.

Materials and methods

Site characteristics and soils

The study was conducted in Northeast Thailand at the Land Development Department research station located 15 km from Nakhon Ratchasima, Korat province (15° N, 102° E). The choice of the site was based on previous studies that highlighted a high resistance to root penetration, particularly in the subsoil (Hartmann et al., 1999).

Northeast Thailand is characterised by a semi-arid tropical climate with a distinct rainy season from April to October and a dry season from November to March. The average annual rainfall is 1020 mm. Annual and monthly rainfall is highly variable on a year to year basis (min = 599 mm and max = 1446 mm for the period 1971–1998). Rainfall generally exceeds evaporation during the growing season and there are at least 3 months of dry season in the year. Water stress is frequent for most crops, not only during the dry season, but also between the rainfall events, due to the rapid drainage and inherent low water holding capacity of the soil.

The soil at the experimental site is of a sandy texture and belongs to the *Nam Phong* soil series (Haimsrichat et al., 1993). It is classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) and Arenic Acrisol (FAO classification). Selected chemical and physical characteristics of the soil are presented in Table 1. Field measurements of resistance to penetration are presented in Figure 1 along with the gravimetric water content under wet and dry conditions.

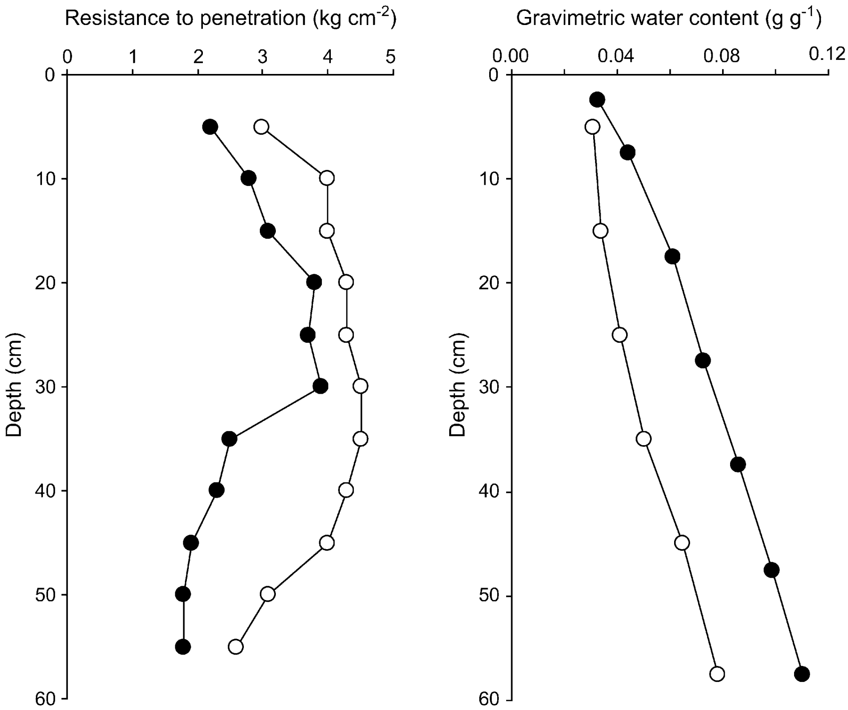

Figure 1. Resistance to penetration measured in the field with a pocket penetrometer. Both wet (–•–) and dry (–○–) conditions are presented with respective gravimetric water content profiles (average and standard deviation associated).

Experimental design

The study site has been under an annual cropping regime since clearing of native vegetation that includes ploughing to a depth of approximately 20 cm and the subsequent formation of ridges on which the crop was planted. Beneath the tilled topsoil, field observations indicate the presence of a subsoil with high penetration resistance that decreased with depth (Figure 1). The study consisted of two treatments, namely, (a) continuous stylo (CS) where *S. hamata* was grown for 24 months before being converted to maize (*Zea mays* cv. SW 3601) production in the third year; and (b) stylo-maize rotation (SM) where *S. hamata* was grown for 4 months, followed by maize for 4 month, followed by a 4 month ley annual weedy pasture over the dry season. The latter treatment represents current farming practice. The experimental design was a randomised complete block design with 10 plots of 48 m^2 in area (8 × 6 m) for each treatment.

During the maize cropping phase, the soil was ploughed to a depth of 20 cm and ridges 10 cm high and 30 cm wide were formed. Ridging was undertaken to prevent flooding of the crop during heavy rainfall events which are common during the wet season.

Maize was established at a density of 50,000 plants ha^{-1} with an average of 3 plants per stand on ridge. Stylo was established at a density of 30,000 plants ha^{-1} with an average of 2 plants per stand on ridge, as generally practised by farmers.

Five replications of CS and SM were destructively sampled to describe the stylo root system and macropore density after 24 and 4 months, respectively. The remaining 5 replicates for each treatment were used to describe these attributes at the end of the 3 year cycle. Macropore density of the compact layer was quantified in the field 2 weeks after harvesting stylo for both treatments.

In the final year of the study (year 3), maize (*Zea mays* cv. SW 3601) was grown using identical agronomic practices in the 10 remaining plots (SM = 5; CS = 5). Maize root systems were described for each treatment at the flowering growth stage. Total aboveground biomass, grain yield, cob number and weight were measured on each plot at physiological maturity.

Macropores quantification

Porosity is usually investigated through micromorphological observations of impregnated blocks or thin

Table 1. Selected soil physical and chemical properties of the Arenic Acrisol used in the study

	Particle size distribution (g kg^{-1}) mesh equivalent diameter in μm								OC (%)	pH		CEC (cmol$_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2–20	20–50	50–200	200–500	500–100	1000–2000	2000–5000		H_20	$CaCl_2$		Mean	SD
10–15 cm	37	63	60	381	357	81	19	2	0.19	4.5	4.0	0.9	1.48	0.07
25–35 cm	53	64	61	399	331	75	17	<1	0.17	4.6	3.9	1.2	1.69	0.05
40–50 cm	88	65	69	347	324	96	11	<1	0.08	4.8	3.9	2.3	1.67	0.05

OC is organic matter content; pH was measured in both water (pH_W) and 0.01 M $CaCl_2$ (pH_{CaCl2}) using 1:5 soil:solution; CEC is cation-exchange capacity; BD is dry bulk density measured in the field using cylinders; SD is standard deviation ($n = 5$).

sections (Krebs et al., 1994; Bruand et al., 1996; Stewarts et al., 1999). These studies give accurate results but are time consuming and therefore not suited to large area observations. On the other hand, Volkmar (1996) observed that only macropores of equivalent diameter greater than 500 μm resulted in a positive correlation with root growth. As these macropores are visible to the naked eye, we estimated their density in the field using a similar methodology to that described by McKenzie and Jacquier (1997). Assuming that the main physical barrier to root proliferation occurs at 20–40 cm (Hartmann et al., 1999), we limited our quantification of macropore to this layer.

The method used to quantify macropores consisted of initially excavating and removing the top 30 cm of the profile and then preparing a horizontal area (1 m^2) that is situated in the middle of the compact layer. When preparing a large and relatively flat soil surface in the field, it is often difficult to ensure that the structure and the porosity are not disturbed (i.e., by smearing of soil in some places). In our case, the structure of the soil is inherently unstable even after ploughing and subject to rapid slumping under wet conditions (Hartmann et al., 2002). With respect to the compact layer (20–40 cm depth) that is below the ploughed layer and therefore unaffected by tillage operations, it has a massive structure and is therefore resistant to changes in structure and porosity due to disturbance (Bruand et al., 2004). The structure of this layer is characterised by a close arrangement of fine sand that presents high resistance to deformation in the non-ploughed state. The clay, even though in small quantities, acts as a cementing agent under dry conditions, thereby increasing the soil strength and resistance to structural deformation when disturbed. Observations were made under dry conditions in order to limit any possible disturbance to the structure. The surface was carefully cleaned using a soft brush and air-blown in order to highlight macropores and decaying roots, and vertical macropores visible to the naked eye were quantified, independently of their shape or origin. Observations were undertaken on 5 plots per treatment with 25 replications per plot (125 macropore assessments for each treatment). There is no consensus on the definition of a macropore, especially on the range of equivalent diameter (Luxmoore et al., 1990). In this study, we consider all pores of equivalent diameter > 500 μm as macropores.

Root system description

Tardieu (1988) concluded that the commonly used criteria of Lv (root length per unit of volume) and HMDR (half distance between neighbouring roots) are not adequate parameters for assessing root system structure in studies on the effects of soil tillage or compaction due to the horizontal variability of Lv. In order to characterize root systems as water and mineral element sinks, we used a mapping method, adapted from Tardieu and Manichon (1986), which consisted of mapping the frequency of roots on a 100×60 cm^2 vertical face (three plants for stylo, five for maize) using a 2×2 cm grid. A trench was dug perpendicular to the planting line for stylo and along the planting line for maize. Descriptions of the root distribution in each of the treatments consisted of determining the presence or absence of at least one root in each of the 2×2 cm cells for the entire exposed profile face. Using this approach, problems of root clumping due to the presence of cracks or holes is avoided. Results were expressed as root frequency impact (percentage of cells occupied by at least a root) for each depth (Nicoullaud et al., 1994; Tardieu and Manichon, 1986).

Statistical analysis of all data was undertaken using the software package Statistix 7 (Analytical Software, 2000).

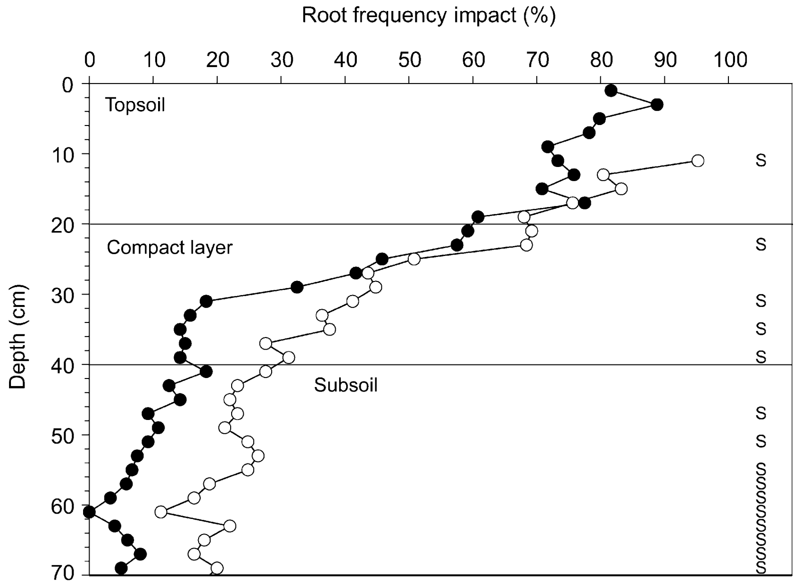

Figure 2. Root frequency impacts of *Stylosanthes hamata*, 4 months (–•–) and 24 months (–○–) after establishment. 'S' indicates significant difference for the considered depth ($n = 5$, $P < 0.05$).

Results

Root frequencies of stylo

Figure 2 presents root frequencies of stylo after 4 and 24 months as a function of depth from the top of the ridge down to 70 cm. The height of the ridges changed with time due to their collapse and settling, and after 24 months, the original ridges were no longer evident. From 0 to 15 cm depth, roots were observed in approximately 80% of the cells in both the 4 and 24 month samples. Whilst there was a decline in root frequency over this depth interval, regardless of sampling time, there were no significant differences between the CS and MS treatments. Conversely, over the 15–30 cm depth interval, frequency values decreased linearly with depth for both treatments (from 80 to 20–30%). However, root frequencies were significantly ($P < 0.05$) higher under the 24 month CS treatment when compared to the 4 month SM treatment and these differences persisted to 70 cm (Figure 2).

Root frequencies of maize

The root frequencies of the maize crop established in the third year of the study under the CS and SM treatments are presented in Figure 3. The shape of the frequency distribution curves was similar for both treatments with 80–90% root frequency being recorded in the 0–10 cm depth interval with no significant differences between treatments. However, in the 10–70 cm depth interval, maize root frequencies were significantly ($P < 0.05$) higher under the CS treatment when compared to SM treatment.

Macropore density in the compact layer

The presence of vertically-oriented macropores under the two treatments as a result of stylo production is presented for each treatment in Figure 4. Significantly ($P < 0.05$) higher macropore densities were observed under the CS treatment when compared to the SM rotation treatment. Variability between individual replications of the same treatment was considerably higher under the SM treatments when compared with the CS treatment with coefficients of variation of 73 and 24%, respectively. Variability related to uncertainty of the method is difficult to estimate but considering that all replicates were processed under the same conditions, the variability is assumed to be the same for both treatments.

Discussion

Ability of stylo to develop roots in compacted soil layers

Regardless of species, root development and proliferation was greatest in the topsoil and ridge regions

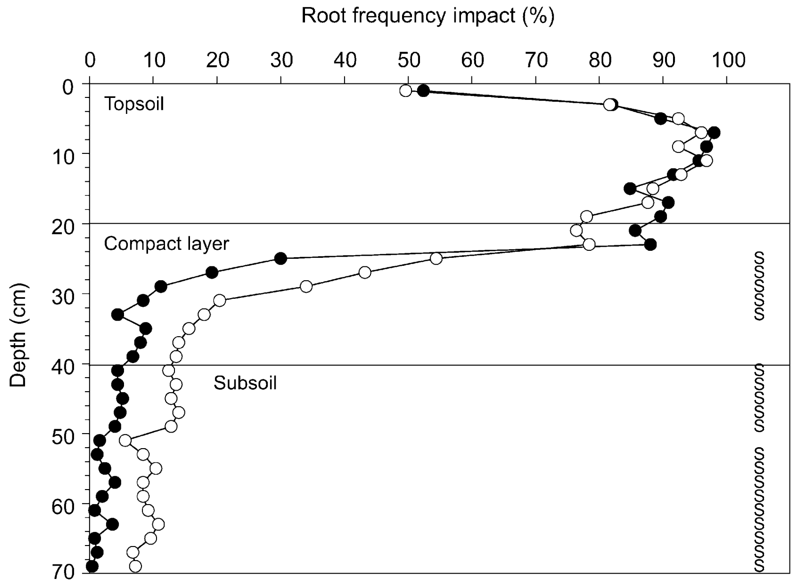

Figure 3. Root frequency impacts of a maize crop (in the third year of the study). Stylo/maize rotation (–○–) and continuous stylo treatment (–●–). 'S' indicates significant difference for the considered depth ($n = 5$, $P < 0.05$).

(Figure 2–3) where penetration resistance is lowest (Figure 1). However, root frequency rapidly declined when the compact layer was encountered. At depths below 40 cm, resistance to root growth decreased and therefore root frequency tended to remain constant with increasing depth. This confirms the presence of a physical barrier that impeded root proliferation at depth and previous observations made on these soils (Hartmann et al., 1999).

By comparing the root distribution of maize and stylo it is possible to assess the ability of the individual species to either create or utilize existing macropores to overcome a compacted layer. In the case of maize, most of the root system is confined to the topsoil (Figure 3). However, below this region of low soil strength relatively few roots was evident indicating the inability of the species to pass through the compact layer. It is well recognized that maize roots develop in zones of low resistance (Tardieu and Manichon, 1987) and within existing macropores and cracks (Hatano et al., 1988; McMahon and Christy, 2000). Nevertheless, after 2 years of continuous stylo, roots were able to penetrate this compacted layer, this being evidenced by the significantly higher root frequencies observed. This result supports previous observations made by Bajracharya et al. (1996) on the ability of stylo root systems to penetrate dense compacted layers. The fact that there is a significant increase in root frequencies between the 4 and 24 month would suggest that penetration of this layer does not occur during short rotations and that even stylo experiences difficulties in penetrating this layer in the short term. Under non-limiting physical conditions stylo roots have been observed to develop to significant depth (> 3 m) thereby allowing this species to actively grow during dry periods as is common to the semi-arid tropics (Williams and Probert, 1984).

Subsoil macropore creation by roots of stylo

Macropore density was observed to be significantly higher after continuous stylo when compared to the current advocated 4-month legume/crop rotation that is practiced by farmers in the region (Figure 4). This would suggest that the development of macropores within a compacted layer by stylo is time dependent. The assumption is made that most of the macropores that developed were due to the presence of stylo roots as evidenced by the old or decaying roots. However, it is possible that some of these macropores were created through greater biological activity associated with the continuous crop cover associated with stylo (Stirzaker and White, 1995). This result confirms the augmentation of macropores in deeper layers that Bridge et al. (1983) observed in the topsoil. Bridge et al. (1983) also observed that macropore development under a *Stylosanthes hamata* pasture increase significantly only after several years of continuous pasture indicating the importance of time. This would

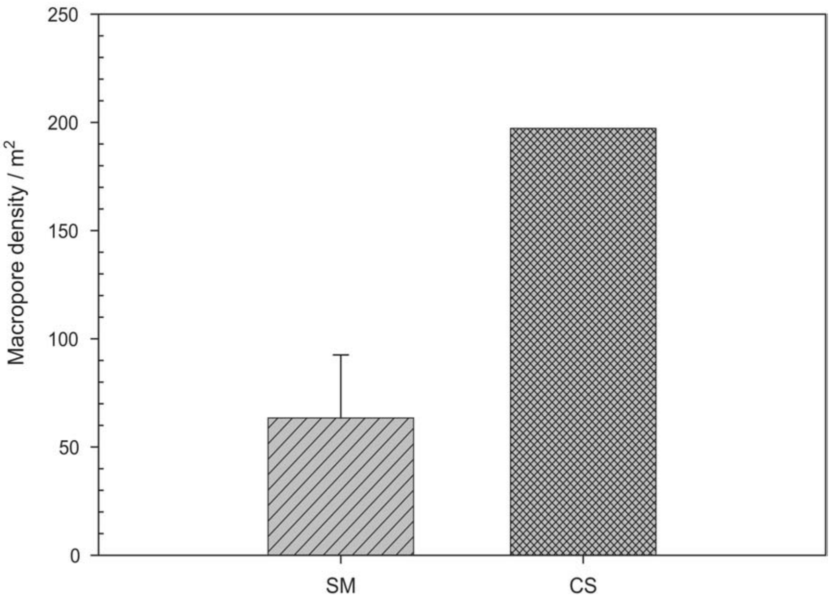

Figure 4. Vertically oriented macropore density of compact layer for the continuous stylo (CS) and stylo/maize rotation (SM) at 24 and 4 months, respectively. Vertical bar is the Least Significant Difference between treatments at $P = 0.05$ (LSD).

in part explain why Ruaysoongnern and Aitken (1980) were not able to observe any amelioration in soil structure in their studies with short rotation stylo and convention crops in Northeast Thailand. The results from the current study would suggest that in order to achieve structural amelioration of compacted layers on soil in Northeast Thailand using *Stylosanthes*, a minimum rotation of 2 years of continuous legume should be advocated.

The main advantage of macropores developed by roots when compared to subsoiling, is that they are stable and will persist. Characteristics of the compact layer on these sandy textured soils is that they have a massive structure, no aggregation and insufficient clay to allow structure maintenance through swelling/shrinking cycles. Mechanically modifying the structure of these resistant layers enhances porosity in the short term. However, due to the unstable nature of the structure of these soils the benefits of mechanical modification rapidly degenerates after a significant rainfall event as water acts as a lubricant thereby facilitating slumping (Hartmann et al., 2002). In contrast, macropores developed from root channels are very stable because they develop in the stable structure of the compact subsoil and likewise the compaction exerted by the roots when growing within this layer makes them locally very coherent (Dexter, 1987; Bruand et al., 1996).

Benefits to the subsequent maize root system

The root frequencies of maize were significantly higher in and under the compact layer after CS treatment (Figure 3). The structural improvement that continuous stylo induced in the compact layer benefited the rooting ability of the subsequent maize crop. Maize was able to develop a higher density of roots in the compact layer using macropores created by decaying roots of the previous stylo and also in the subsoil under this physical barrier where the resistance to penetration decreased (Figure 1). These results support the findings of Stirzaker and White (1995) and Stewart et al. (1999).

The fertility of sandy soils is inherently low and under high intensity rainfall regimes that are typical of most tropical climates this is exacerbated further through leaching of nutrients beyond the rooting depth of most plants. Therefore it is plausible that a plant with deep-rooting characteristics or one that would enhance rooting characteristics for the subsequent crop, represents a potential means of effecting better soil nutrient recycling and stored water utilization that is reflected in greater crop productivity (Salako et al., 2002). In the present study there was no measured improvement in maize yield after continuous stylo. The lack of a significant response in the yield of maize could be attributed to the unusual growing conditions that prevailed towards the end of growing season, thereby masking any benefits associated with improved rooting. Successive heavy rainfall events resulted in the water table rising to near the surface during the critical flowering stage thereby preventing any water stress from occurring in the shallow-rooted MS treatments, whilst hydromorphic conditions may have affected the deep-rooted CS treatments. In addition, other confounding factors that are independent of soil structure may have affected the yield responses these including low soil pH (Noble et al., 1997), microbial interactions and hormonal effect (Passioura, 1991). Shehu et al. (1997) showed in some cases, that intercropping maize with *Stylosanthes hamata* results in a reduction of maize yield when compared to pure stands of maize. Although they worked in a different cropping system (intercropping instead of rotation), where competition for water (Williams and Probert, 1984) and for nutrients (Haynes and Swift, 1984) are factors to take in consideration, they did not find any stylo beneficial effect on maize yield.

Conclusion

As a pasture species, *Stylosanthes hamata* is able to grow on degraded soils with low pH and is economically profitable as it provides forage for livestock. The advantages of stylo with respect to its ability to provide nitrogen to subsequent crops is well known and farmers of the Northeast routinely grow it in their crop rotations (Ruaysoongnern and Aitken, 1980).

This study demonstrated that *Stylosanthes hamata* is able to develop a significant quantity of roots both in and below a compact physical barrier and that is time dependent (e.g., at least 2 years under continuous stylo). Decaying roots of stylo create a large number of macropores that represent significant amelioration of the compact layer. Subsequent crops are able to take advantage of this amelioration through the development of a more extensive root system in and under the compact layer. This amelioration of compacted layers by roots represents a potential low cost means of improving crop productivity and face water stresses during dry spells.

The only way to grow crops on these degraded upland soils has long been to mechanically break the compact layer. However, due to the unstable nature of these soils they revert in less than one year to their original compact state through slumping during the rainy season with the corresponding collapse of macropores. By using stylo as a low-cost soil amelioration technique, the development of stable macropores can be achieved thereby enhancing the potential productivity of these soils. Further agronomic evaluations of the benefits associated with increased macroporosity through root drilling under adverse climatic conditions (i.e., water limiting conditions) is required. The potential effect of the structure amelioration on the yield should be investigated independent of the provision of nitrogen effects. Even if soil pH did not change significantly during the three years of the study, the risk of accelerated acidification (Noble et al., 1997) should also be considered as a potential limiting factor with respect to promoting stylo on these soils.

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References

Angers D A and Caron J 1998 Plant-induced changes in soil structure: Processes and feedbacks. Biogeochemistry 42, 55–72.

Bajracharya R M, Cogle A L, Lal R, Smith G D and Yule D F 1996 Surface crusting as a constraint to sustainable management on a tropical alfisol: II. Strength characteristics during crust development. J. Sust. Agric. 8, 45–63.

Bridge B J, Mott J J, Winter W H and Hartigan R J 1983 Improvement in soil structure resulting from sown pastures on degraded areas in the dry savanna woodlands of northern Australia. Aust. J. Soil Res. 21, 83–90.

Bruand A, Cousin I, Nicoullaud B, Duval O and Begon J C 1996 Backscattered electron scanning images of soil porosity for analyzing soil compaction around roots. Soil Sci. Soc. Am. J. 60, 895–901.

Bruand A, Hartmann C, Ratana-Anupap S, Sindhusen P, Poss R and Hardy M 2004 Composition, fabric and porosity of an Arenic Haplustalf in Northeast Thailand: Relation to penetration resistance. Soil Sci. Soc. Am. J. 68, 185–193.

Cresswell H P and Kirkegaard J A 1995 Subsoil amelioration by plant roots - The processes and the evidence. Aust. J. Soil Res. 33, 221–239.

Dexter A R 1986 Model experiments on the behaviour of roots at the interface between a tilled seed-bed and a compacted sub-soil. III. Entry of pea and wheat roots into cylindrical biopores. Plant Soil 95, 149–161.

Dexter A R 1987 Compression of soil around roots. Plant Soil 97, 401–406.

Haimsrichat P, Boonsompoppan B and Trisuwan N 1993 Characterization of soil series established in the northeastern region and their interpretation for uses. Soil Survey and Classification Division, LDD, Ministry of Agriculture and Cooperation, Thailand 314.

Hartmann C, Poss R, Janeau J L, Bourdon E, Lesturgez G and Ratana-Anupap S 2002 Use of the granular material theory to interpret structural changes in a sandy soil. *In* 17th World Congress of Soil Science, Bangkok, Thailand, 14–21 August, 2002.

Hartmann C, Poss R and Singhatat V 1999 Soil compaction and plant growth in Northeast Thailand: The case of the Nam Pong soil serie. *In* Ecoregional Approaches to Natural Resources Management in the Korat Basin, Khon Kaen, Thailand, 1999. Ed IRRI/Khon Kaen University.

Hatano R, Iwanaga K, Okajima H and Sakuma T 1988 Relationship between the distribution of soil macropores and root elongation. Soil Sci. Plant Nutr. 34, 535–546.

Hatano R and Sakuma T 1990 The role of macropores on rooting pattern and movement of water and solutes in various field soils. *In* 14th Congress of Int. Soc. Soil Sci., Kyoto, 1990. pp. 130–135.

Haynes R J and Swift R S 1984 Amounts and forms of micronutrient cations in a group of loessial grassland soils of New Zeland. Geoderma 33, 53–62.

Kheoruenromne I, Suddhiprakarn A and Kanghae P 1998 Properties, environment and fertility capability of sandy soils in Northeast Plateau, Thailand. Kasetsart J.: Natural Sci. 32, 355–373.

Krebs M, Krestzschmar A, Babel U, Chadoeuf J and Goulard M 1994 Investigations on distribution patterns in soil: Basic and relative distributions of roots, channels and cracks. Dev. Soil Sci. 22, 437–449.

Luxmoore R J, Jardine P M, Wilson G V, Jones J R and Zelazny L W 1990 Physical and chemical controls of preferred path flow through a forested hillslope. Geoderma 46, 139–154.

Mamman E and Ohu J O 1997 Millet yield as affected by tractor traffic in a sandy loam soil in Borno State, Nigeria. Soil Tillage Res. 42, 133–140.

McKenzie N and Jacquier D 1997 Improving the field estimation of saturated hydraulic conductivity in soil survey. Aust. J. Soil Res. 35, 803–825.

McMahon M J and Christy A D 2000 Root growth, calcite precipitation, and gas and water movement in fractures and macropores: A review with field observations. Ohio J. Sci. 100, 88–93.

Miller C, Anning P, Winter W and Wildin J 1991 Developing and managing pastures. *In* Sown Pastures for the Seasonally Dry Tropics. Eds. I J Partridge and C P Miller. pp. 25–34. Queensland Department of Primary Industries, Brisbane.

Nakamoto T 1997 The distribution of maize roots as influenced by artificial vertical macropores. Jap. J. Crop Sci. 66, 331–332.

Nambiar E K S and Sands R 1992 Effects of compaction and simulated root channels in the subsoil on root development, water uptake and growth of radiata pine. Tree Physiol. 10, 297–306.

Nicoullaud B, King D and Tardieu F 1994 Vertical distribution of maize roots in relation to permanent soil characteristics. Plant Soil 159, 245–254.

Noble A D, Cannon M and Muller D 1997 Evidence of accelerated soil acidification under *Stylosanthes*-dominated pastures. Aust. J. Soil Res. 35, 1309–1322.

Oikeh S O, Chude V O, Carsky R J, Weber G K and Horst W J 1998 Legume rotation in the moist tropical savanna: managing soil nitrogen dynamics and cereal yields in farmers' fields. Exper. Agricult. 34, 73–83.

Panichapong S 1988 Soil and water resources in Northeast Thailand. *In* Soil, Water and Crop Management Systems for Rainfed Agriculture in Northeast Thailand. Eds. C Pairintra, K Wallapapan, J F Parr and C E Whitman. pp. 2–13. USDA, Washington D.C.

Passioura J B 1991 Soil structure and plant growth. Aust. J. Soil Res. 29, 717–728.

Pillai U P and McGarry D 1999 Structure repair of a compacted vertisol with wet-dry cycles and crops. Soil Sci. Soc. Am. J. 63, 201–210.

Ragland J and Boonpuckdee L 1987 Fertilizer responses in Northeast Thailand: 1. Literature review and rationale. Thai J. Soils Fert. 9, 65–79.

Ruaysoongnern S and Aitken R L 1980 Nitrogen fixation by cultivars of *Stylosanthes hamata* in two upland soils from northeastern Thailand. Thai J. Agric. Sci. 13, 291–301.

Salako F K, Tian G and Kang B T 2002 Indices of root and canopy growth of leguminous cover crops in the savanna zone of Nigeria. Trop. Grasslands 36, 33–46.

Shehu Y, Alhassan W S and Phillips C J C 1997 The effect of intercropping maize with *Stylosanthes hamata* at different row spacings on grain and fodder yields and chemical composition. Trop. Grasslands 31, 227–231.

Stewart J B, Moran C J and Wood J T 1999 Macropore sheath: quantification of plant root and soil macropore association. Plant Soil 211, 59–67.

Stirzaker R J and White I 1995 Amelioration of soil compaction by cover-crop for no-tillage lettuce production. Aust. J. Agric. Res. 45, 553–568.

Stirzaker R J, Passioura J B and Wilms Y 1996 Soil structure and plant growth: Impact of bulk density and biopores. Plant Soil 185, 151–162.

Tardieu F and Manichon H 1986 Caractérisation en tant que capteur d'eau de l'enracinement du maïs en parcelle cultivée. I. - Discussion des critères d'étude [French]. Agronomie 6, 345–353.

Tardieu F and Manichon H 1987 Conséquences de l'état du profil cultural sur l'enracinement: cas du maïs [French]. *In* Soil compaction and regeneration. Eds. G Monnier and M J Goss. pp. 131–143. Balkema, Rotterdam, The Netherlands.

Tardieu F 1988 Analysis of the spatial variability of maize root density. II. Distances between the roots. Plant Soil 107, 267–272.

Volkmar K M 1996 Effects of biopores on the growth and N-uptake of wheat at three levels of soil moisture. Can. J. Soil Sci. 76, 453–458.

Williams J and Probert M E 1984 Characterization of the soil-climate constraints for predicting pasture production in the semi-arid tropics. *In* Proceeding of the International Workshop on Soils, Townsville, Queensland, Australia, 12–16 September 1983.