Consequences of slotting on the pore characteristics of a sandy soil in northeast Thailand

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Abstract

In the sandy soils of northeast Thailand, root development is generally limited to the topsoil (0–20 cm depth) but a simple slotting intervention (20–40 cm) significantly increased the root frequency in the slotted material (E_{slot}) compared with the undisturbed subsoil (E horizon). The aim of this study was to investigate the consequences of slotting on the soil structure by analysing at different scales the pore characteristics of the original soil profile and of the soil material inside the slot. These characteristics were studied using bulk density measurements, image analysis of thin sections and mercury porosimetry. Our results showed that the total porosity of the E horizon and E_{slot} material was similar when measured in 100 cm^3 cylinders, but that the pore size distribution had been changed by slotting. The unaltered E horizon contained mainly small pores characterized by a narrow distribution related to close packing of the sand grains, associated with some biological macropores probably with poor continuity as they did not contain roots despite their size. On average, pores were larger in the E_{slot} material, with a broader distribution resulting from looser packing of the sand grains but with fewer biological macropores. Although slotting reduced the number of biological pores, the

looser packing appeared to be more favourable to root development than the presence of macropores in the E horizon. Finally, the comparison of the porosity in the different horizons with the porosity of the E_{slot} material, indicated the significance of the closeness of the sand packing on root development.

Introduction

Sand-dominated soils are widespread in the tropics and constitute an important economic resource for agriculture despite their inherent low fertility (FAO, 1975). They occupy a large area in the uplands of the densely populated northeast Thailand sandy plateau (Ragland & Boonpuckdee, 1987). In their pristine state, these soils supported climax forest communities originally dominated by climax *Dipterocarp* forests. About 40 years ago, they started to be extensively cleared for timber and agriculture. When used for agricultural production, their productivity has declined rapidly (Kheoruenromne *et al.*, 1998). These soils are acidic to depth (pH about 4.0 in $CaCl_2$) with a low cation-exchange capacity (CEC < 2 $cmol_c$ kg^{-1}) and therefore have a low nutrient supplying capacity. Roots are confined within a small soil volume hindering nutrient and water uptake when both are in limited supply in this region with erratic rainfall. Hampered root development is attributed to a compact subsoil layer (Imsamut & Boonsompoppan, 1999) highly resistant to penetration (**Bruand** *et al.*, 2004).

This situation is typical of many regions with sand soils. Subsoil compaction is an increasing problem and deep-ripping or subsoiling does not, or only temporally, improve biomass yield and rooting depth (e.g. Ouwerkerk & Raats, 1986; Kayombo & Lal, 1993; Busscher *et al.*, 2002; Munkholm *et al.*, 2005; Sinnett *et al.*, 2006). However, deep tillage restricted to a limited volume of soil seems to be a more efficient option. In South African sandy soils with subsoils highly resistant to root penetration, vertical mulching appears to be an efficient tillage technique to improve physical properties (Meyer *et al.*, 1992). For several Australian problem soils (e.g. saline clays), slotting was reported to be a promising technique to improve physical properties and root development (Jayawardane *et al.*, 1995). Slotting is the creation of narrow parallel bands of soil loosened by deep tillage. It has the additional advantage of maintaining the overall strength of the compacted layer so that tractors do not sink into the profile and initiate subsoil recompaction. The studies of Jayawardane *et al.* (1995) were confined to heavy textured soils and did not address the issue of compacted layers in sandy soils. In the sandy soils of northeast Thailand, Hartmann *et al.* (1999) showed that slotting significantly increased the rooting depth and the yield of legume/maize rotation crops. During two successive years, these authors systematically observed much greater root development in the slotted material (20–40 cm) than in the surrounding undisturbed subsoil, where no roots were found below 30 cm. *Stylosanthes*, a deep rooting legume, was able to extend roots into the B horizon below 40 cm but in contrast maize explored only the ploughed A_p and the E_{slot} material. The dramatic yield increase observed in maize after slotting during a dry year characterized by several dry spells during the growing period showed that the slotted layer retained sufficient water and nutrients to ameliorate limiting conditions.

Improved root development after tillage in sandy soils is generally attributed to a decrease in bulk density (Bennie & Botha, 1986) or to the existence of large voids like cracks or biopores sufficient to enable root penetration despite adverse conditions overall (Bengough & Mullins, 1990; Tardieu, 1994). However, Hartmann *et al.* (1999) did not observe any major discontinuity of the solid phase in the soil profile or any significant difference in bulk density between the slot material and the surrounding undisturbed subsoil, which could be linked with improved root development. Therefore, the effect of slotting on the structure of the subsoil remained unclear, as well as the ways in which these structural changes could affect root development. But a more efficient adaptation of the slotting technique to different sandy soils should result from an improved understanding of the relations between the characteristics of porosity in sandy soils and subsequent root development. The aim of our study reported here was to investigate the consequences of slotting on the soil structure by analysing at different scales the pore characteristics of the original soil profile and of the soil material inside the slot.

Materials and methods

Site characteristics and soils

The study was conducted in northeast Thailand at the Land Development Department research station located in Joho, 15 km from Nakhon Ratchasima, Korat province (15°N, 102°E). This region covers an area of 170 000 km^2 that is inhabited by more than 20 million people, 80% of them farmers. Northeast Thailand has 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 (1971–1999) with high inter-annual variability, ranging from 599 to 1446 mm; the average temperature is 26.2 °C, ranging from 22.7 °C in December to 29.7 °C in April. The soil type at the study site is a sandy soil of the *Nam Phong* soil series (Haimsrichat *et al.*, 1993). It is classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Taxonomy) or an Arenic Acrisol (FAO classification). It was recognized as exhibiting a high resistance to root penetration in the upper subsoil (**Bruand** *et al.*, 2004). In these low organic matter soils (<1% in topsoil) with 6 months of water deficit, biological activity is low: no earthworms were found and only fungus-eating termites were regularly observed. Selected chemical and physical characteristics of the soil are presented in Table 1.

Experimental design and sampling

In a field at Joho experimental station, 6 × 8 m plots were randomly distributed, with five replicates of control and slotting treatments. In the control treatment, the subsoil (below 20 cm depth) was left undisturbed. In the slotted treatment, slots 9 cm in width were opened every 40 cm along the planting lines at 20–40 cm depth in the E horizon identified by **Bruand** *et al.* (2004) as the horizon with the greatest resistance to penetration (Figure 1). Slotting was done manually with a small spade at the onset of the rainy season. The A_p material (0–20 cm depth) was first removed. Then, the E horizon was broken into fragments of < 1 cm^3 *in situ* working from the top downwards with a narrow spade, resulting in a loose granular material (E_{slot} material) from 20 to 40 cm below the soil surface. The A_p material was then put back, covering the slot without any mixing between topsoil and subsoil. Finally, the 0–20 cm A_p of the control and the slotted treatments was disk-ploughed with a motorized cultivator. A crop rotation of a legume (*Stylosanthes*) followed by maize (*Zea mays* cv. SW 3601) was established for 2 years to assess the impact of slotting on crop performance. Rooting in the control remained confined to the topsoil (0–20 cm), but slotting resulted in a systematic and significant increase in root development: the root frequency was similar in the slotted material (20–40 cm) and in the topsoil (Hartmann *et al.*, 1999). However, the effect of slotting on plant development depended on the rainfall regime with the yield of maize and the biomass of *Stylosanthes* benefiting only in conditions of water deficit. After the second maize harvest, pits were dug in areas where both improved root development and increased yield were represented. In these areas, undisturbed samples were taken from the A_p horizon between (10 and 20 cm depth); E horizon and slot (E_{slot}) between 25 and 35 cm depth; and B_t horizon between 40 and 50 cm depth (Figure 1).

Bulk density

Bulk density was measured in triplicate in each plot using cylinders 100 cm^3 in volume (BD_{cyl}). Bulk density was also measured on small undisturbed clods 2–6 cm^3 in volume (BD_{clo}) by using the kerosene method (Monnier *et al.*, 1973) with 15 replicates per layer.

Pore morphology

In each plot, undisturbed samples 12 × 6 × 4 cm^3 were collected in the A_p, E, and B_t horizons and in the E_{slot} material. The samples were oven-dried at 40 °C for a week and impregnated with a polyester resin diluted with styrene monomer (30% by volume) at room temperature under low vacuum (5 kPa). A hardener and a fluorescent compound (Uvitex OB at 1 g L^{-1}; Ciba-Geigy, Hawthorne, NY, USA) were added to the resin mixture, (Hartmann *et al.*, 1992). Resin polymerization and hardening were complete after 4 weeks and polished sections (5 mm thick) were prepared for each block, for each horizon, and representative blocks were selected after binocular observations. Then, image analysis was carried out with the VISILOG® software. For each block, three pictures (7.7 × 5.7 mm) were taken with a CCD camera (Tarcus CV-M300) under reflected UV light, where pore space appears bright on a dark background. Each individual image was digitized in a rectangular grid of 768 × 576 pixels, with a spectral resolution of 256 grey levels and a spatial resolution of 10 µm per pixel. Grey level images were then thresholded into binary images.

For each binary image, we first established the porosity spectrum that gives the proportion of voids according to pore equivalent size (S_e in µm) (Kribaa *et al.*, 2001). The process was a progressive pore infilling with hexagonal structuring elements of increasing size, using the 'opening' morphology mathematical operation (Serra, 1982). The porosity spectrum was used to determine the modal size ($S_{e,m}$) that corresponds to the maximum of the pore size distribution curve. Then, we determined the pore shape (Lamandé*et al.*, 2003; Fox *et al.*, 2004; Lima *et al.*, 2006) using the elongation index (EI) defined as:

$$EI = P^2/4 \times \pi \times SA$$

where P is the perimeter of the pore and SA the surface area of the pore.

Three shape classes were determined: rounded, irregular and digitate pores (Bullock *et al.*, 1985) with EI < 5; 5 < EI < 15; and EI > 15, respectively. Only pores larger than 30 µm were processed.

Mercury porosimetry

Mercury (Hg) intrusion was performed with a porosimeter (Micromeritics 9320, Norcross, GA, USA) operating at pressures between 4 and 2000 kPa, enabling the study of pore-size distributions with equivalent diameters (D_e) ranging from 360 to 0.006 µm. Small clods (about 1 cm^3 in volume) from all of the horizons were selected and dried at 105 °C for 24 h before Hg intrusion. Three clods were studied from each horizon. In these soils consisting mainly of rigid quartz grains and limited amount of clay, three classes of pores namely A, B and C were identified and interpreted, respectively, as pores resulting from the arrangement of the sand particles alone, pores within the clusters of coarse silt material present between the sand particles, and pores resulting from the packing of the clay particles within clay coatings on sand particles (Coulon & **Bruand**, 1989; Fiès & **Bruand**, 1998).

Results and discussion

Bulk density and macroporosity

Our results showed a smaller BD_{cyl} and BD_{clod} in the A_p horizon than in the E horizon and no significant difference between the E and B_t horizon (Table 2). Because of the small difference in particle size distribution between the three horizons (Table 1), the smaller BD_{cyl} and BD_{clod} recorded in the A_p horizon was attributed to tillage effects (Coulon & **Bruand**, 1989). Table 2 shows that the E and B_t horizons had similar total porosity measured with cylinders (39% using a particle density of 2.65 t m^{-3}) and there were small differences between BD_{cyl} and BD_{clod} (0.016 t m^{-3}). On the same experimental plots, Lesturgez *et al.* (2004), found in the E and B_t horizon a low density of macropores (65 m^{-2}) consisting of termite galleries of < 5 mm diameter. These macropores have only a limited probability of occurrence when sampled by the cylinders (100 cm^3 in volume) and their occurrence within the clods (some cm^3 in volume) would have been rare. Therefore, in the A_p horizon, the macropores responsible for the difference between BD_{cyl} and BD_{clod} were most likely due to tillage whereas in the E and B_t horizons they were most likely due to biological activity (termites).

Porosity differences resulting from sand grain packing in the undisturbed soil profile

According to Coulon & **Bruand** (1989), the porosity measured within the clods can mainly be related to that resulting from sand grain packing. Thus, the similar BD_{clod} recorded for the E and B_t horizons could result from similar compact packing with a resulting low porosity of 33%. On the polished sections, magnification was selected to observe only the large pores resulting from the sand packing. The porosity was 11.8, 13.8 and 24.0% in the A_p, E and B_t horizons, respectively (Figure 2). In the three horizons, the pore size (S_e) distribution was unimodal (Figure 3) with slight differences with respect to the width of the peak: narrow for A_p and E horizons (S_e from 70 to 130 µm and 30 to 170 µm, respectively), and larger for the B_t horizon (S_e from 70 to 320 µm). Indeed, the main difference between horizons was in the occurrence of the largest pores: the A_p and B_t horizons showed pores with S_e up to 450 and 800 µm, respectively, while not a single pore with S_e > 170 µm was observed in the E horizon. Therefore, despite similar pore volume measured on clods in E and B_t, pore size distribution differed significantly, suggesting a difference in sand packing.

Shape of the pores observed on polished blocks (Figure 3) can provide information on the origin or functionality of the pores. Digitate pores are often associated with the packing of aggregates or sand grains and therefore are usually connected in 3D (Bullock *et al.*, 1985; Pagliai *et al.*, 1998). In contrast, round pores are generally associated with compacted situations and with low connectivity when biological activity is absent as it is the case in our plots (Fox *et al.*, 2004; Lima *et al.*, 2006). Digitate pores were nearly absent in the A_p and E horizon (<1% of the thin section surface) and exceeded half of the total porosity in the B_t horizon (14.8% of the surface). In the E horizon, more than half of total porosity consisted of round pores compared with less in the A and B horizons (8.3% compared with 6.3 and 6.0% of the surface, respectively). Moreover, the rounded pores were only small (Figure 3). Therefore, the E horizon was characterized by the absence of preferential pathway for root development and most of the pores were probably the result of compact sand grain packing.

Analysis of the Hg intrusion curves (Table 3) showed that the total pore volume ($V_{p,m}$) ranged from 0.162 to 0.224 cm^3 g^{-1}, corresponding to the E and A_p horizons, respectively. In all layers, the pores of class A resulting from sand grain packing corresponded to 83–85% of $V_{p,m}$, but the size distribution was different with $D_{e,A}$ equal to 55, 28, and 53 µm for the A_p, E and B_t horizons, respectively. This result confirmed the close packing of sand grains in the E horizon observed on thin sections. Fiès & **Bruand** (1990) showed that the pores were accessible to Hg for a value of D_e that was several times smaller than the average size of the pores measured by image analysis. Thus, the pores of class A identified by Hg porosimetry corresponded to the pores with $S_{e,m}$ = 90, 70 and 170 µm on polished sections in the A_p, E and B_t horizons, respectively (Figure 3).

The results obtained on samples of clod size or smaller, with methods based on different principles, are consistent. These results show that, despite a similar sandy texture, the three horizons exhibit large differences in pores characteristics. As expected, the A_p horizon had the largest pore volume and pore size due to tillage operations. The lower porosity of the E horizons was characterized by the absence of large or digitate pores. Large pores generally occupy only a limited volume but they are the most important for water transfer (Hallaire & Curmi, 1994; Lima *et al.*, 2006) and root development (Doussan *et al.*, 2003; Pagliai *et al.*, 2004). In the absence of these large pores, the pore volume of the E horizon seemed to result from the packing of sand grains. Moreover, this packing seemed to be particularly close and homogeneous. Therefore, the E horizon acted as a physical barrier hampering root development mainly because of absence of any discontinuities in the solid phase and the unfavourable pore size distribution.

Porosity of the soil material in the slot

The results presented in Table 2 show that compared with the E horizon, the E_{slot} material had similar BD_{cyl} but higher BD_{clod}. The higher porosity of E_{slot} at clod size was confirmed on polished sections with a total porosity of 23.3% compared with 13.8% in the E horizon. Pores in the slotted material were characterized by a broad distribution of dimensions with S_e mainly between 50 and 350 μm ($S_{e,m}$ = 110 μm) associated with several pores with 350 < S_e< 800 μm, with the neighbouring E horizon having a narrow distribution of small pores with S_e < 110 μm (Figure 3). Compared with the E horizon, the slot material was also characterized by a dramatic increase in the shape index (Figure 2). Large digitate pores represented approximately one-third of total porosity measured on polished blocks in the E_{slot} (6.8% of the total surface), while they were nearly absent (<1%) in the E horizon. These results show that slotting created large discontinuities which had high connectivity as indicated by their high digitate shape. Consequently, these discontinuities provide the preferential pathways used by roots to develop in the slot material. Investigation with Hg injection showed that $V_{p,m}$ in the E_{slot} material (0.202 $cm^3\ g^{-1}$) was greater than in the E horizon (0.162 $cm^3\ g^{-1}$) due to a higher $V_{p,A}$ (0.175 compared with 0.135 $cm^3\ g^{-1}$), $V_{p,B}$ and $V_{p,C}$ being similar. Therefore, this method confirmed that the increase in porosity was associated with a broader size distribution of large pores approx. > 30 μm. In a soil consisting mainly (Figure 4) of regularly packed rigid quartz grains, our results indicate that slotting resulted in the formation of larger digitate pores suggestive of locally loose packing of sand grains as identified on the binary images of the polished sections (Figure 5). Despite this looser and irregular packing at the scale of sand grains, the BD_{cyl} in the E_{slot} material was not greater than in the E horizon. This is most probably because: (i) the density loosened soil was likely to be locally increased ahead of the cutting ring of the cylinder and (ii) the biological pores (termite galleries) were partly destroyed during slotting and this volume was replaced by the porosity resulting from looser packing of sand grains. Despite similar total pore volume at cylinder scale (100 cm^3), pore size distribution and sand packing were different in the E horizon and E_{slot}.

In our experiment, slotting was hand-made to avoid topsoil and subsoil mixing and to enable the description of the relations between changes in physical soil characteristics and root development. But in farm fields, only mechanical slotting would be technically and economically feasible; moreover it would also have the advantage of incorporating material with higher organic matter content to the unfertile subsoil, probably increasing the positive effect of slotting on plant yield. Jayawardane *et al.* (1995) presented different equipment for slotting clayey soils which could be adapted to sandy soils. They suggested that the optimum slot configuration (width, depth and spacing) should depend on soil and crop types. But a width of approximately 10 cm seems optimal for very different soil types, as it was successfully used in clayey soils (Heilman & Gonzalez, 1973; Farina & Channon, 1988; Blackwell *et al.*, 1989) and sandy soils (Hartmann *et al.*, 1999). Therefore, only slotting depth and spacing should be adapted to different soil and plant type. Slotting depth should be related (i) to the maximum depth to which root can develop and (ii) to the volume needed to supply enough water and mineral elements and ameliorate limiting conditions compared with control. On the other hand, slotting spacing must be adapted to the distance between planting rows and to the ability of roots to develop laterally and explore several slots simultaneously. The very limited recompaction observed in our experiment was attributed to (i) fast root development after slotting, which stabilized the large digitate pores and (ii) to the high friction between grains in subsoil layers, which avoided natural collapse. To maintain the loose structure over the long term, and thus to limit the need of regular slotting, organic matter incorporation (stabilizing large digitate pores) or the use of a V-shape slot (increase the friction between sand grains and walls of the slot) as described by Kirby & Blackwell (1989) are possible options.

Conclusion

Our results show that in the sandy soils studied, similar bulk density measured with cylinders can result from different packing states having various potential for root development. The E horizon was characterized by the presence of a majority of small pores with a narrow size distribution resulting from dense and regular packing of rigid sand grains with only a few poorly connected large pores resulting from biological activity (termites). Compared with the E horizon, in the E_{slot} material pores with a larger size distribution and digitate shape occupied a significantly greater volume; in contrast, the biological galleries occupied a smaller volume in the slotted soil. After slotting no pore was observed during profile observations, but the close packing of the E horizon had been loosened. Because roots were located in the E_{slot} material (Hartmann *et al.*, 1999) and not in the neighbouring E horizon, the looser packing of sand grains appeared to be more favourable to root development than the presence of a few biological galleries. Comparison of the porosity of the E_{slot} material with the porosity in the different horizons suggests that the extent of root development in a sand-dominated soil is mainly related to the closeness of packing of the sand grains.

Acknowledgements

This work formed part of the research program funded by the Department of Technical and Economic Co-operation (DTEC), funded and operated in Thailand by the Thai Land

Development Department (LDD) and the French Research Institute for the Development (IRD) under the approval of the National Research Council of Thailand (NRCT). This work also received financial support from the Department '*Soutien et Formation*' (DSF) from IRD and the technical assistance from several colleagues from the French National Institute for Agronomical Research (INRA).

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Tables & Images

Figure 1 Schematic representation of the soil profile

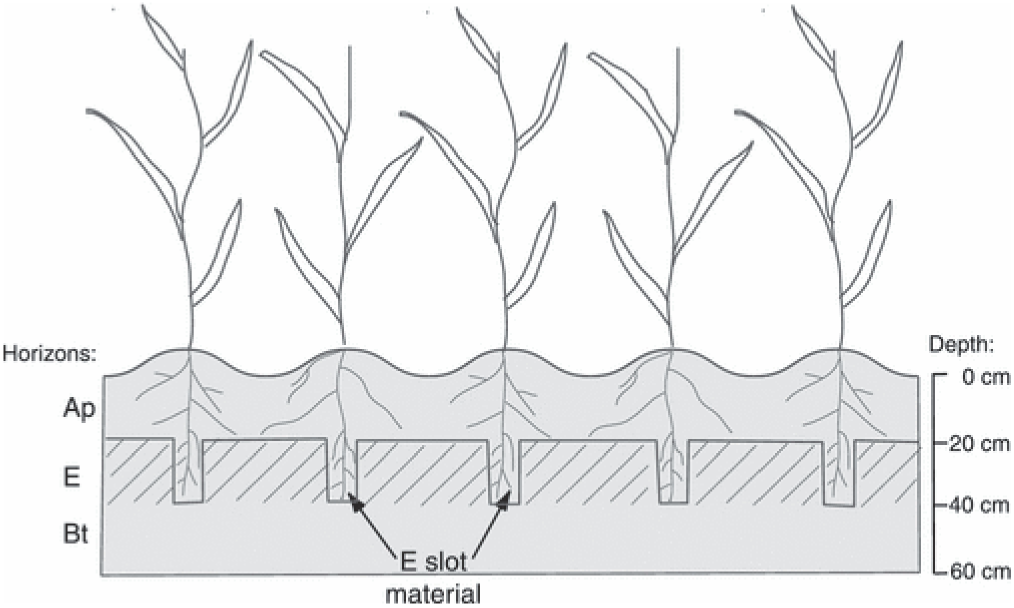

Figure 2 Shape of the pores and related porosity measured on polished blocks in the A_p, E, and B_t horizons and in the E_{slot} material (round: Elongatum index (EI) < 5; intermediate: 5 < EI < 15; digitate: EI > 15).

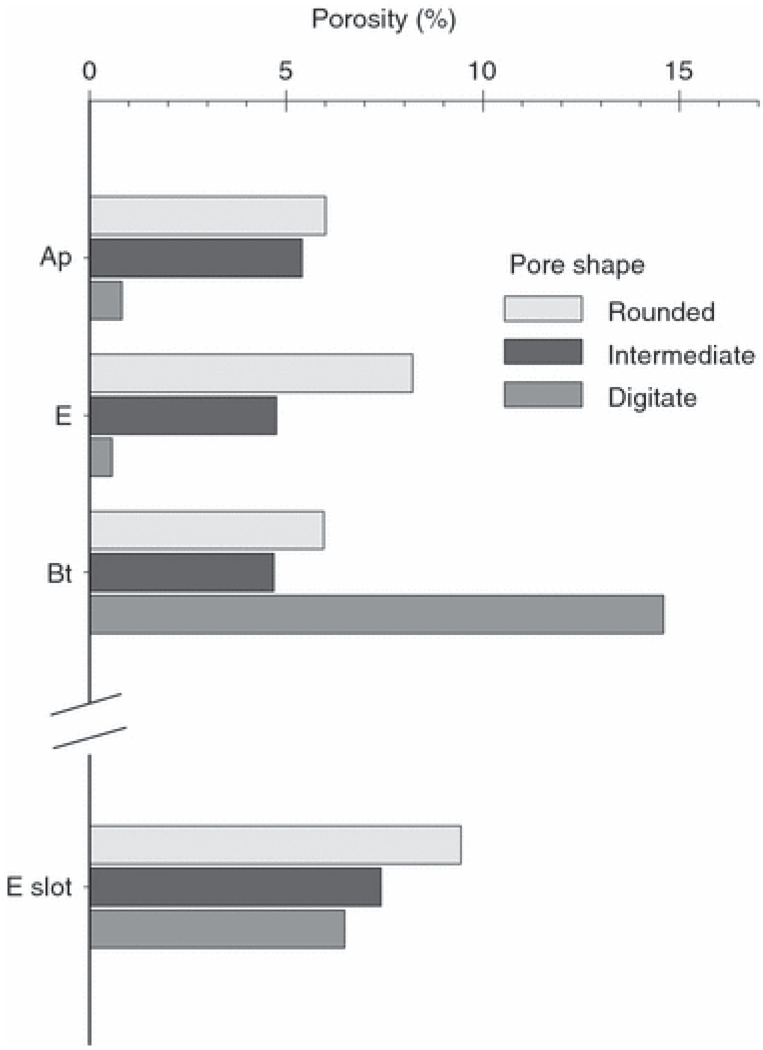

Figure 3 Pore size distribution expressed as equivalent diameter (S_e in µm, $S_{e,m}$ being the modal pore equivalent diameter) in the A_p, E, and B_t horizons and in the slot material (E_{slot}).

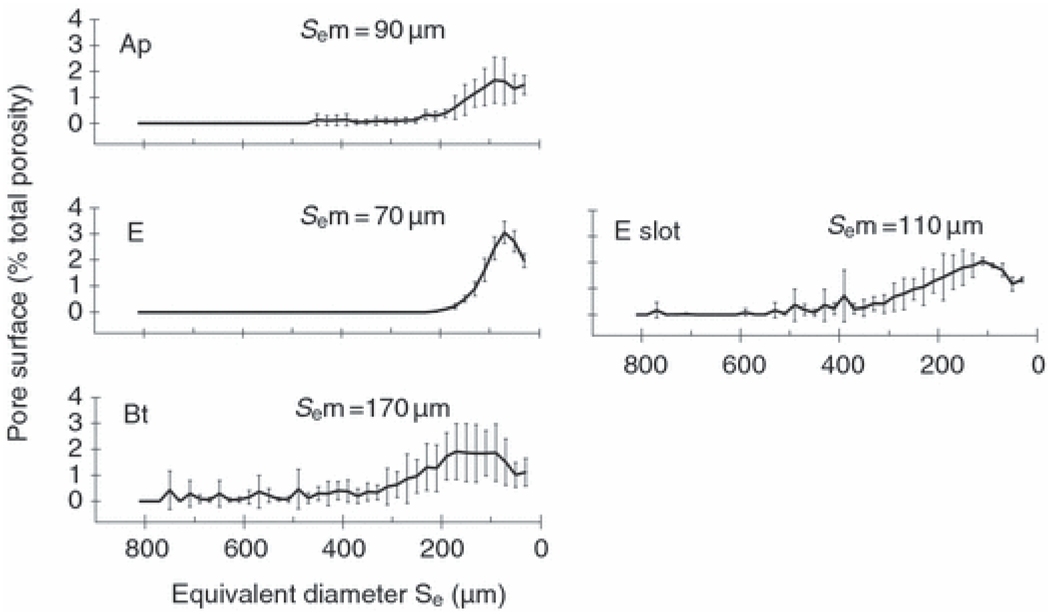

Figure 4 Cumulated mercury intrusion curve (a) and its derivative curve (b) recorded for the E horizon (–○–) and E_{slot} material (–●–).

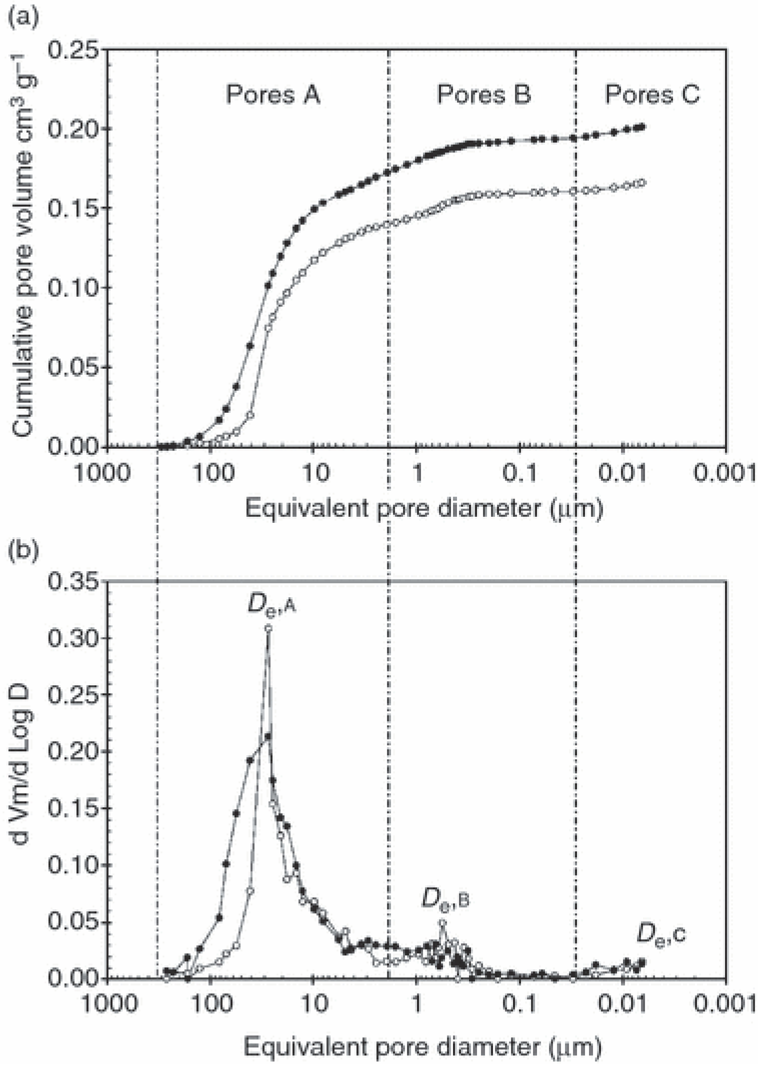

Figure 5 Binary image of the porosity in the E horizon (a) and in the E_{slot} material (b) (pores analysed by image analysis are in white, the original size was 7.7 × 5.7 mm^2).

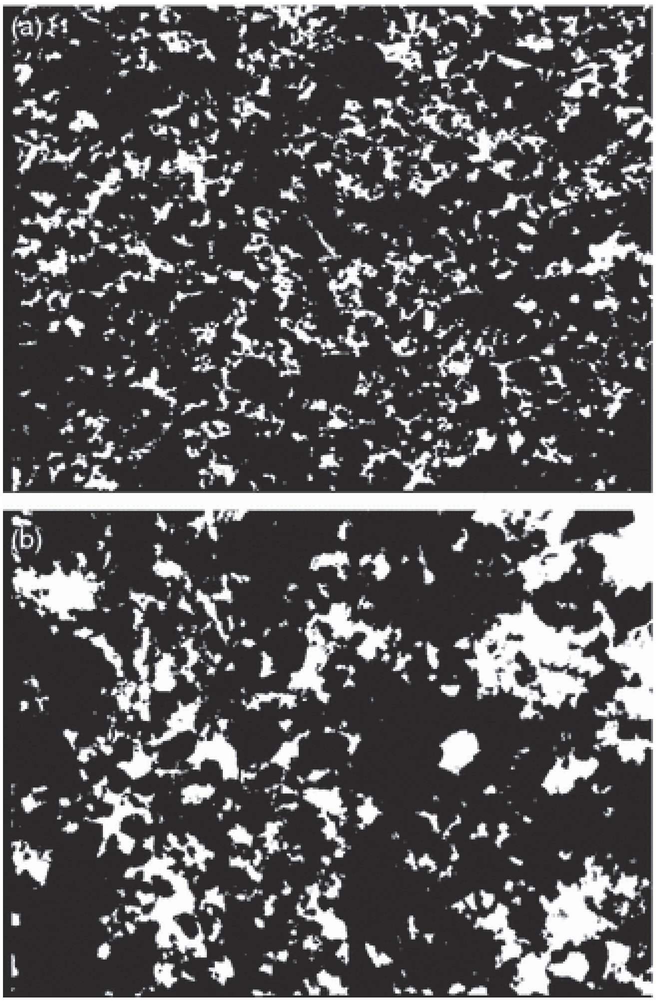

Table 1 Selected soil physical and chemical properties of the Arenic Acrisol at the study site

Horizon	**Particle size distribution (g kg^{-1})**								**OC (g kg^{-1})**	**CEC ($cmol_c$ kg^{-1})**
	<2	***2–20***	***20–50***	***50–200***	***200–500***	***500–1000***	***1000–2000***	***2000–5000***		
					μm					
A_p (0–20 cm)	37	63	60	381	357	81	19	2	1.9	0.9
E (20–40 cm)	53	64	61	399	331	75	17	0	1.7	1.2
B_t (40–60 cm)	88	65	69	347	324	96	11	0	0.8	2.3
OC, organic carbon content; CEC, cation-exchange capacity.										

Table 2 Bulk density (t m^{-3}) determined with cylinders (BD_{cyl}) and clods (BD_{clod}) in the different horizons (A_p, E and B_t) and slot material (E_{slot}). For each method of bulk density measurement, means followed by the same letter are not significantly ($P > 0.05$) different

	BD_{cyl} (t m^{-3})		BD_{clod} (t m^{-3})	
	Mean	**SD**	**Mean**	**SD**
A_p	1.48 a	0.07	1.63 a	0.02
E	1.62 b	0.03	1.78 b	0.01
B_t	1.62 b	0.02	1.78 b	0.01
E_{slot}	1.64 b	0.03	1.73 c	0.03

Table 3 Pore volumes measured by mercury porosimetry[a]

Horizon	Total pore volume		Class of pores					
			A with: 360 < D_e < 2 μm		B with: 2 < D_e < 0.03 μm		C with: 0.03 < D_e < 0.006 μm	
	$V_{p,m}$	SD	$D_{e,A}$	$V_{p,A}$	$D_{e,B}$	$V_{p,B}$	$D_{e,C}$	$V_{p,C}$
	$cm^3 g^{-1}$	$cm^3 g^{-1}$	μm	$cm^3 g^{-1}$	μm	$cm^3 g^{-1}$	μm	$cm^3 g^{-1}$
A_p	0.224	0.004	55	0.192	0.8–0.4	0.027	–	0.006
E	0.162	0.002	28	0.135	0.8–0.4	0.021	–	0.005
B_t	0.142	0.003	53	0.154	0.8–0.4	0.020	–	0.013
E_{slot}	0.202	0.003	28	0.175	0.8–0.4	0.022	–	0.005

[a]$V_{p,m}$ is the total volume of pore; SD is the standard deviation of the replicate measurements of $V_{p,m}$; $D_{e,A}$, $D_{e,B}$ and $D_{e,C}$ are the modal equivalent-pore diameter of the pore classes A, B and C, respectively (see Bruand & Prost, 1987); $V_{p,A}$, $V_{p,B}$ and $V_{p,C}$ are the pore volume of the pore classes A, B and C, respectively; A_p Horizon: 10–20 cm depth layer; E Horizon: 25–35 cm depth layer; B_t Horizon: 40–50 cm depth layer.