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Soil structure and rooting[1]

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Abstract

The rooting of crops affects productivity. Poor roting can be a significant constraint. Rooting depends on the soil structure, taken in a broad sense to include structure, porosity, and consistency. Simple methods can be used to identify the structural units within a cultivation profile that could influence root growth: compacted volume, plough pan, pedological discontinuties, etc. Similarly, there are several approaches for a morphological characterization and quantification of rooting. The two methods are combined to assess physical constraints related to soil characteristics and tillage. A study of the cultivation profile is useful for evaluating the appropriateness of various cropping operations.

Introduction

For site characterization and monitoring experiments, samples are collected *in situ* and analyzed in the laboratory (Webb and Coughlan, 1989; Nualsri Kanchanakool, 1989). The procedure also requires a large number of field observations and measurements. Such observations include a study of the

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structural state of the horizons in the root zone. The definition of the soil structure is extended to porosity and consistency. The three properties which influence a large number of important rooting and crop production processes are:

- *Emergence:* Emergence is poor or delayed if the seedbed is too compacted or if the clod size does not allow sufficiently close contact between the soil and seed.
- *Water and nutrient supply:* This depends not only on soil moisture, but also on the type of root colonization, which in turn is influenced by the structural state.
- *Aeration:* At field capacity, soil pores should hold approximately 10% volume of gas, of which 10% is oxygen (Dexter, 1988). The cultivation profile should also provide favourable drainage conditions.

An earlier paper discussed the main forms of degradation of the cultivation profile (Valentin, 1988). The present paper aims to provide further information on the characterization of the soil sturcture and its relation to rooting.

Characterization of the soil structure

Structure of the tilled horizon

The description of a cultivation profile should answer two questions:

- Have the objectives of the cultivation operation under study been achieved?
- What is the response of rooting to the resulting physical conditions?

The description of a cultivation profile is linked to that of the soil profile. However, particular attention should be paid to:

- horizontal variability of the structure;
- discontinuity due to soil tillage.

In practice, it is useful to refer to an established checklist that describes various types of structure. For example, de Blic (1976a) used the following checklist in Côte d'Ivoire:

Shape of aggregates

- single grained,
- fragmentary,
- massive with blocky substructure,
- massive.

Size
- fine to medium,
- medium to coarse.

Grade
- weakly developed,
- moderately developed,
- strongly developed.

The same author distinguished four classes among tilled horizons:
- with dominant fragmentary structure,
- fragmentary to massive structure,
- dominant massive structure,
- exclusively massive structure.

The unfavourable conditions of the last three classes can be attributed to the lifting of massive and cohesive fragments from the underlying horizon, to soil compaction under the weight of tractors, or to inadequate fragmentation due to tillage under conditions which are too dry.

In France, Tardieu and Manichon (1987a) proposed the following classification for structural unit assemblage:
- fragmentary state characterized by the size of the elements (fine earth, centimeter- or decimeter-size clods);
- massive state, possibly with associated cavities and fissures.

These authors distinguished three main types of ploughed horizons. The first type is made up of fine earth and centimetre-size clods. This case is not very common and is observed in plots with little degradation. Compaction can rarely be completely avoided because of the cropping schedules. The second type is characterized by the proximity of compacted blocks and structural cavities. It is observed when the soil is highly compacted before tillage - for example, during the previous harvest. The third type presents a continuous and compact horizon. It is the structural state observed after direct planting on a previously compacted soil.

Regardless of the classification system that is adopted in relation to local conditions, the sketch of the cultivation profile should indicate, in addition to the structural units (Figure 1):
- sharpness of transition,
- the nature of discontinuities due to soil tillage (plough pan, shining surfaces, Plate 1),
- location of organic matter and biological niches,
- rooting pattern (de Blic, 1987; Fritsch and Valentin, 1987; Valentin, 1988).

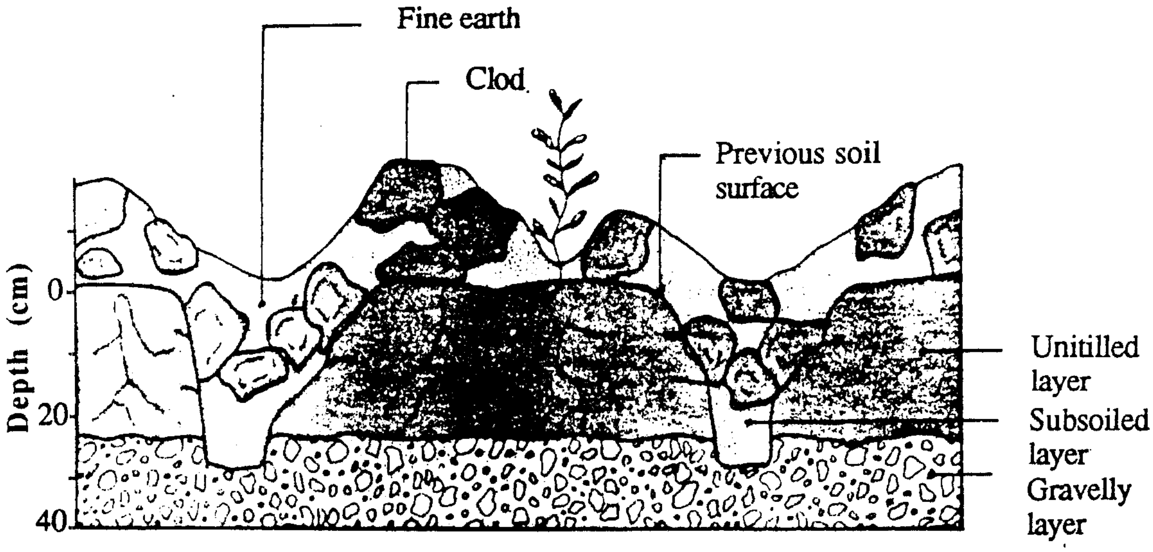

Figure 1. Cultivation profile after clearing and subsoiling on a savanna soil (adapted from de Blic and Moreau, 1977).

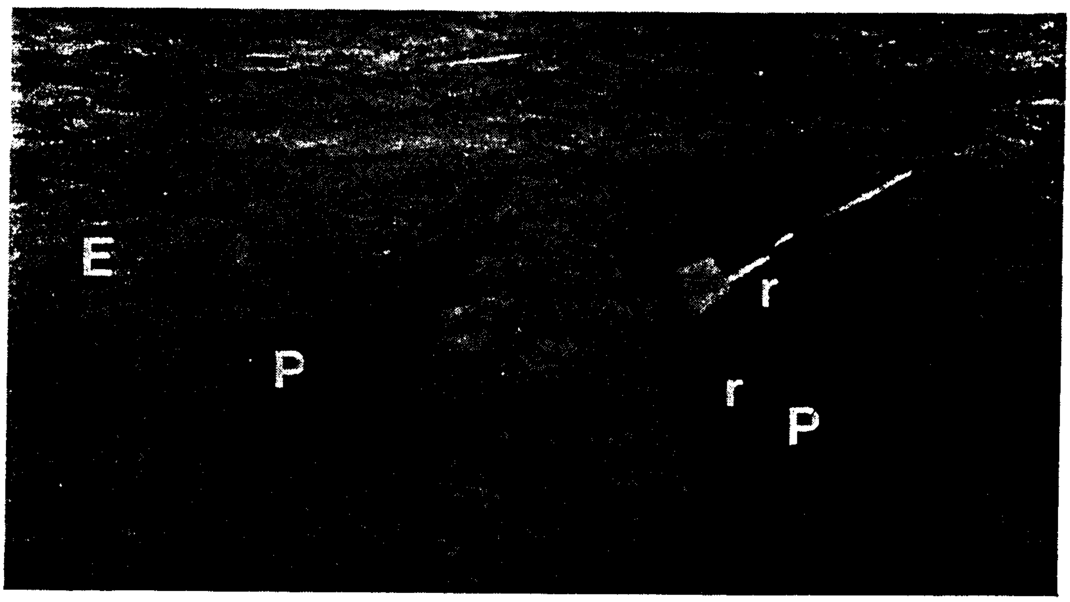

Plate 1. Cultivation profile in Burkina Faso. Note the plough pans (*P*) which resist root penetration (*r*) and the surface crust erosion (*E*).

Porosity

While describing the cultivation profile, inter- and intraclod porosity should be visually evaluated according to a semiquantitative scoring system. Such field observations are indispensable and are often combined with:

- field measurements, using core or excavation methods (Webb and Coughlan, 1989) to evaluate the total porosity of the different structural states identified during the description of the cultivation profile (Figure 2); and
- laboratory measurements, where bulk density is determined on clods (Lenvain *et al.*, 1987; Nualsri Kanchanakool, 1989) and the particle density of processed samples.

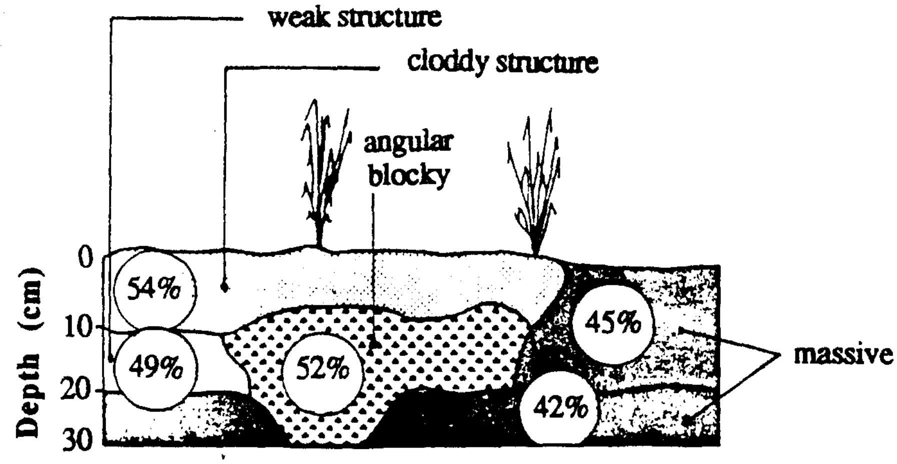

Figure 2. Porosity (%) of different structural units in the cultivation profile of an upland rice crop in the savanna - first year of cultivation after clearing and subsoiling (adapted from de Blic, 1976a).

The two series of measurements are compared to calculate inter- and intraclod porosity.

Consistency

Often, total porosity may not be a sufficient indication of the degree of soil compaction, as it only consists of the packing of particles. According to Webb and Coughlan (1989), there is a strong correlation between compaction and crop yields. Resistance to penetration is measured by various devices. Different types of penetrometers are available. A simple and inexpensive model is described in the appendix. Resistance to penetration generally decreases exponentially as soil moisture increases; each penetrometric profile should therefore be combined with the moisture profile (Figure 3).

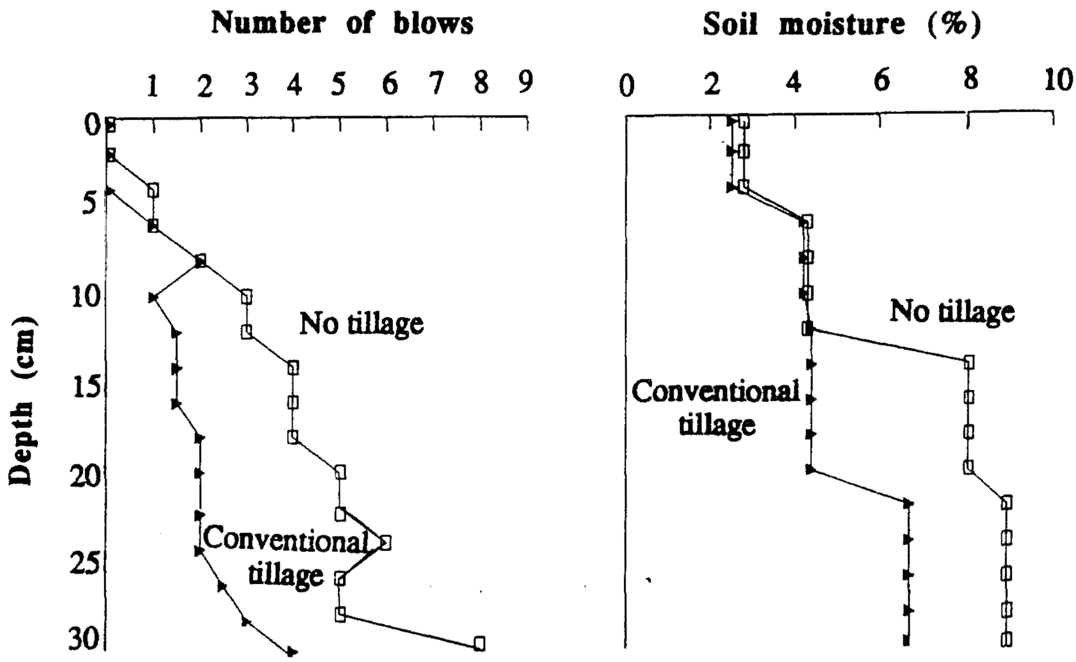

Figure 3. Comparison of penetrometric profiles (number of blows, average of 6 replicates) and soil moisture (% of mass, average of 3 replicates) for two treatments in a pineapple crop on sandy ferrallitic soils: a) without soil tillage and with mulching - harvest stubble on the surface reduces evaporation, and although soil moisture conditions are better, they are still inadequate to loosen the soil; b) with normal soil preparation (ploughing and surface operations) and incorporation of harvest residue - the soil dries more easily but soil tillage reduces resistance to penetration more than the previous treatment (adapted from Camara, 1978).

Study of rooting

Soil scientists often concentrate more on soil than on root observations. However, the establishment of the cultivation profile requires a study of the root system, as this is a vital link for understanding soil-plant relations. For this purpose, it is useful to review certain simple principles.

Characterization of the root system

Identification of root types

Rooting is characterized first by its type (fasciculate or root), and by the number and size of ramifications. The main roots develop from the seed, usually according to positive geotropism, and penetrate vertically into the soil, whereas lateral roots of the first, second, or third order may grow more horizontally.

Variables

Morphological

The area of the soil-root interface is assessed in addition to the maximum rooting depth. The soil-root contact area is calculated on the basis of root diameter. Such measurements should include variations in soil and root volume, depending on the moisture conditions.

Spatial

The main parameters to be considered in assessing the vertical and lateral distribution of roots are:

- density: This is expressed in weight/volume, number of contacts/area, root length/volume, etc; and
- the average distance separating two roots *D*. This variable is particularly important for studies on water supply to plants. It is generally determined from root length/unit volume *L*. The formulas are based on geometric models selected for root distribution. Thus:

$$D = a\,(L)^{-0.5}$$

where a = 1.00, 1.07, or 1.13 (authors cited by Tardieu and Manichon, 1986a).

The distribution of these parameters is generally studied according to depth and distance from the plant row.

Root growth

The preceding parameters can also be studied over time. One of the most common variables is rate of root elongation, expressed in centimetres/day, per root type (root axis, primary lateral, secondary lateral).

Methodology

Visual examination

Visual examination should precede all other measurements, as it determines the characteristics of the sampling (depth, replicates, etc.). It already indicates constraints to the root system, such as the presence of a plough pan. An examination of the roots reveals symptoms for diagnosing stress. Callot *et al.* (1982) give examples of roots that developed ferromanganic sheaths to resist pressure exerted by structural elements. The sheaths, which isolate the roots from their environment, helped evaluate differences in vigour, mainly among fruit trees.

The root profile is sketched on site and compared with the cultivation profile (McSweeney and Jansen, 1984).

Quadrat method

The quadrat method consists of placing a grill with a given mesh size (5 cm) on a vertical profile and counting the number of roots per square. The technique is frequently used for determining the total length of the roots *L* per horizon, and to calculate the average distance between roots *D*. The method was improved by Tardieu and Manichon (1986b) during a study on maize rooting:

- The grill mesh was reduced to 2 cm.
- Readings were taken:
  - o vertically, between two plants;
  - o horizontally, at five levels, within the ploughed horizon (17 cm) and below (30 cm, 60 cm, 80 cm, 100 cm).

Sampling methods

There are two main techniques for taking samples.

- In the first technique, pin boards are placed along a vertical profile that is then removed completely. The root system is carefully washed in the laboratory. If the pins are sufficiently dense - they are generally arranged 10 cm apart - the main root system remains practically intact, and the main morphological characteristics can be studied. The method requires much effort and is not suitable for quantitative studies.
- In the second technique, the samples are removed in vertical or horizontal cores (Chopart and Nicou, 1976). The cores are cut along the horizon or structural unit and washed in water. The technique is difficult to apply in gravel soils. Otherwise it is suitable for quantitative studies. It can be very usefully combined with the quadrat method. The collection of a limited number of samples helps to establish a reliable

relationship between the number of roots observed per square and the weight or length per structural unit.

Influence of physical properties on rooting

Texture

Soils with coarse texture are more easily colonized by roots than clayey soils. According to Callot *et al.* (1982), high sand rates are conducive for root ramification (through increased branching), and hence there is an increase in the quantity of roots.

Structure

Soil structure can offset the effect of texture. A very clayey soil, but one with small aggregates can be colonized as well as a sandy soil. Generally, roots in massive and compacted horizons are scanty (Figure 4), fine, and straight, whereas they are more ramified, twisted, and hairy in soils with a well-developed structure. Crumb or fine blocky structures are the most favourable to rooting (Plate 2). It is particularly useful to study lateral variations in structure within the same tilled horizon. The most massive zones, with few roots, inhibit rooting in the directly underlying layers. Heterogeneity of the surface horizon structure is thus reflected in the root distribution in the nontilled horizons (Tardieu and Manichon, 1986b).

Porosity

Small variations in porosity can bring about large differences in colonization by roots. Callot *et al.* (1982) observed that root dry weight for catstail grass (*Phleum*) increased from 1.3 g to 2.1 g/kg of soil due to a change in porosity from 40 to 45%.

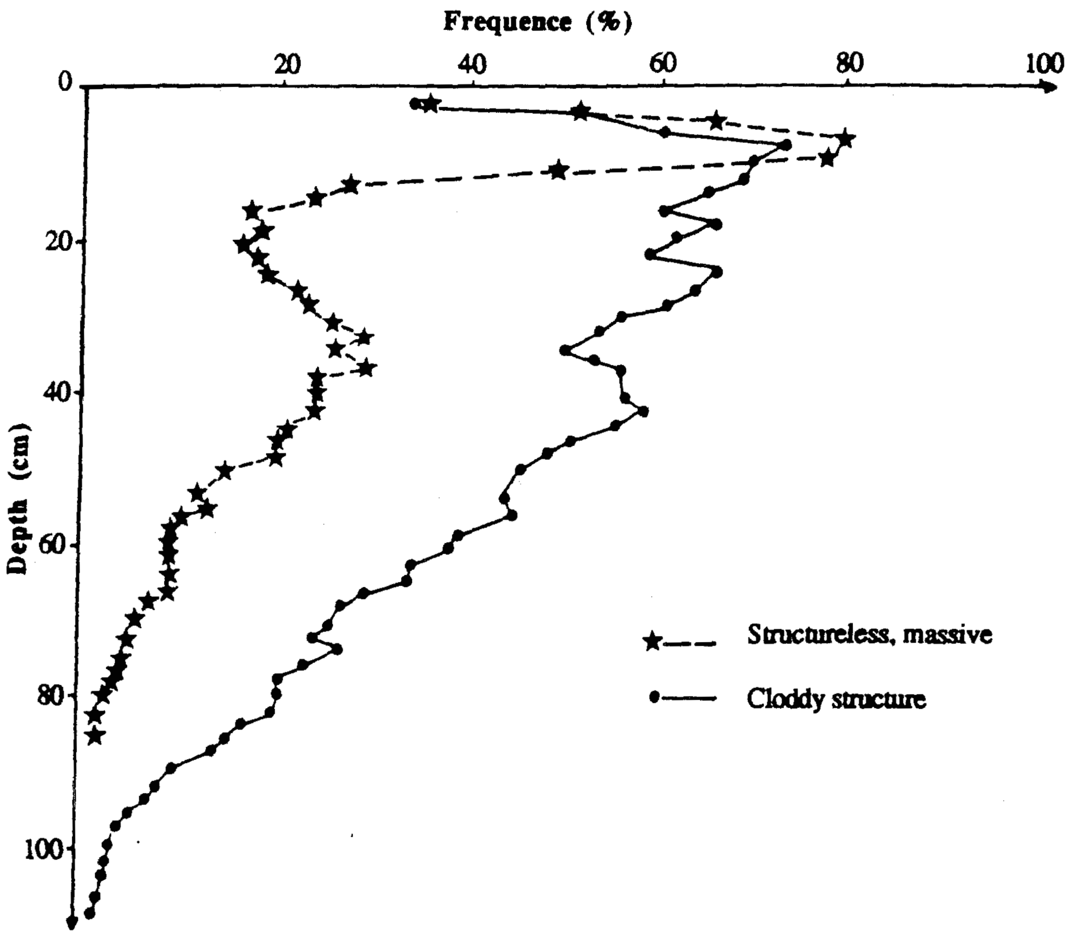

Figure 4. Examples of root profiles at the silking stage in a maize crop, using the grid method. Each point represents the average over 11 replicates of the percentage of 2 x 2 cm squares. At least one impact between the cone and one root occurred.

Consistency or compaction

Porosity provides important information on aeration and water supply to roots, but not on soil consistency. Generally, rooting is influenced more by resistance to penetration than by aeration and soil moistrue (Callot *et al.*, 1982). In order to penetrate, roots require sufficiently large and continuous pores, or have to enlarge smaller pores. Root extension is thus affected even by slight pressure (Russel, 1977). Soil compaction also reduces microporosity, with an adverse effect on drainage and gas exchange. It is therefore important to check compaction during land clearing and other mechanized operations.

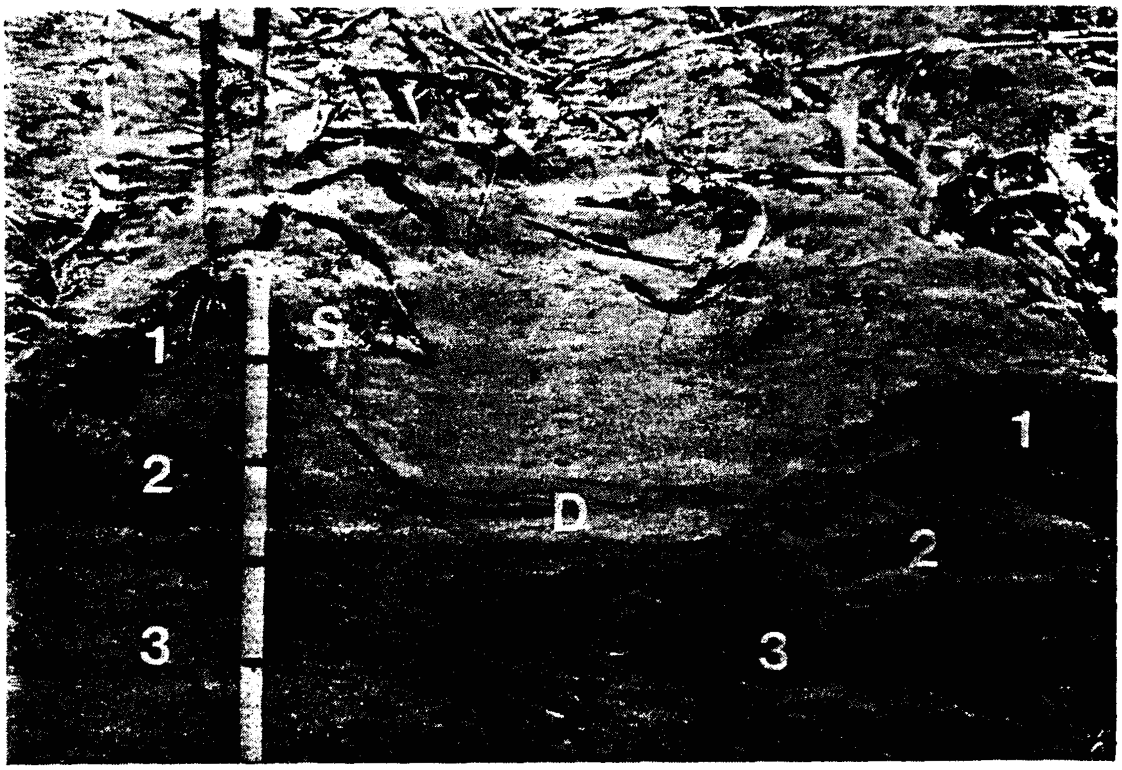

Plate 2. Cultivation profile for maize in Zambia. Note the structural units; the soil in tilled mounds is loose, and has a fine structure, which is easily penetrated by roots; under the tilled mounds, the soil is more compact, and has less root penetration; under the tilled area, the soil is compact, and there is very little root penetration. Note also the surface crust (S) and the runoff (D).

Conclusion

The study of the relationship between soil structure and rooting is a key factor in understanding soil-plant relations, and is often overlooked. The combination of characterization of the soil structure with physical field measurements is useful for analyzing the appropriateness and efficiency of soil tillage operations. Although soil tillage is usually beneficial to rooting, it can nevertheless cause localized compaction. This means that the vertical and lateral distribution of roots rather than their average density should be considered. The more regular the root colonization, the better is the uptake by plants water likely to be.

Appendix

The hammering penetrometer

Objective

To measure resistance to penetration through a vertical soil profile.

Principle

A metallic cone is driven vertically into the soil by hammering, in order to measure the resistance of the soil to penetration by the cone.

Material

Hammering penetrometers are built in accordance with the model illustrated in Figure 1. The instrument is made up of several components having the following characteristics:

- A calibrated lower rod, 1 m long and fitted with an anvil. The markings, set for example at 1-cm intervals, should be engraved rather than painted or stuck, as they last longer. The rod diameter should be between 1.2 and 1.3 of the cone diameter to minimize friction.
- An upper rod, 1 m long, along which the hammer slides. A stop at the top of the rod ensures a uniform dropping height. The stop should be removable so that the hammers can be slipped over the rod. More rods can be joined together to reach depths exceeding 1 m.
- A set of hammers of 0.2, 0.5, 1 kg or more, and up to 20 kg. The selected metal should have a high density. The hammer height should be sufficiently low to minimize friction. The hammer diameter should also be reduced to avoid double readings in case the penetrometer is not maintained in an exactly straight position.
- Cone-shaped probe, with a cross section of 2-3 cm^2 and a 90^{o} angle. The cone should be made of very hard steel. Spare cones should be kept to replace worn cones.

In the given example, the total weight of the rods, anvil, and cone is 2 kg; it varies according to the type of cone.

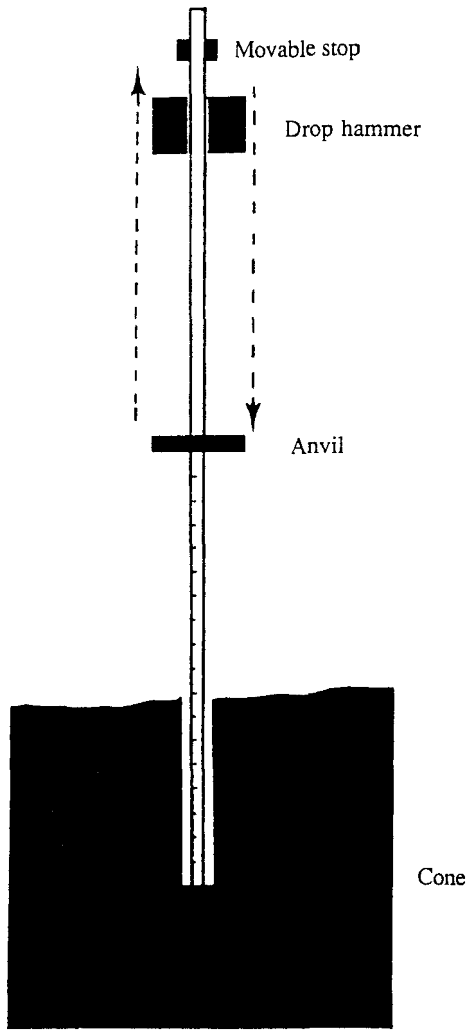

Figure 1. Diagram of a hammering penetrometer.

Procedure

Before starting the measurements, the most appropriate hammer-cone combination should be selected according to the surface horizon, to reduce the number of blows/cm, or inversely the number of centimetres/blow. The combination can be changed for deeper soils, but the penetration depth of the blow should be noted when the components are changed

Resistance can be measured in two ways. Either the penetration depth is measured after each blow, or after *n* blows; or the number of strokes required to reach a given depth are counted. The second method is easier.

While measuring, care should be taken that:

- penetration is vertical;
- the dropping height does not allow the hammer to rebound against the stop.

The measurements are usually carried out by two persons. One person holds the rods straight, drops the hammer, and counts the number of blows. The other checks penetration depth and notes the number of blows per given depth - for example, every 5 cm.

As resistance to penetration varies in inverse proportion to soil moisture, the soil moisture profile should also be established.

These measurements should be combined with a description of the profile in order to link them to the pedological structure and tillage-induced soil discontinuity.

Expression of the results

A preliminary bar chart of the penetrometric profile (Figure 2) should be established in the field, assuming that the same hammer-cone combination is used.

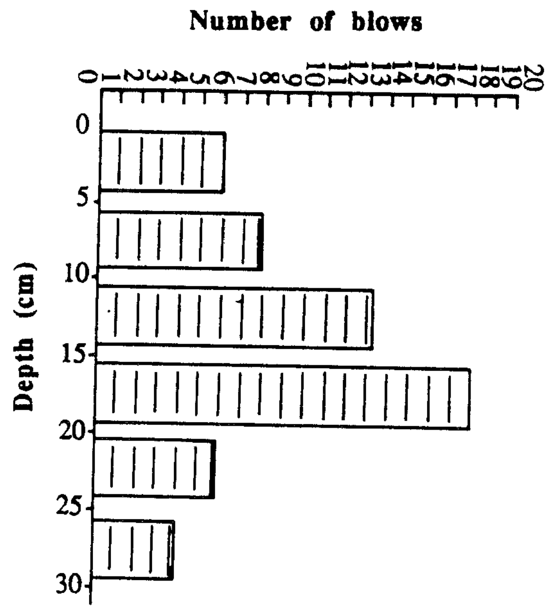

Figure 2. Example of a penetrometric profile established on site. Each bar represents a blow.

Resistance to penetration can be calculated using the following equation:

$$R = \frac{M^2.h.n}{2.(M+m).S.z}$$

where:

- R : resistance to penetration (kg/cm^2)
- M : weight of hammer (kg)
- m : weight of rods, anvil, and cone
- h : height from which hammer is dropped
- S : cross section of the cone (cm^2)
- n : number of blows
- z : penetration depth (cm)

Accuracy

The number of replications depends on soil heterogeneity, required precision, and time-cost factor. For example, three replications are adequate to reveal the existence of a plough pan.

Generally, results of measurements are more closely linked to the resistance to penetration, which are exponential in scale, than to eventual experimental errors, which are arithmetical in scale.

Cost

The cost of the penetrometer depends on the materials used. Commercial models are relatively expensive, but the instrument can be produced locally at lower cost.

Advantages

This type of penetrometer is not very expensive if produced locally. It can be easily transported to the field and only requires two operators. Moreover, it does not disturb the environment.

It is the best way to measure rapidly variations in resistance to penetration within a profile:

- over a given area, measurements can be taken over an entire plot;
- over time, during a crop cycle for example, after a mechanical soil operation.

Disadvantages

This type of measurement can be difficult to carry out on coarse soils or those with many thick or medium-sized roots.

Very often measurements can only be carried out up to a moderate depth, as it is then difficult to extract the cone from the soil.

Conclusion

These measurements also require a visual examination or measurement of other parameters, such as moisture, root density, and bulk density.

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