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The Thermal Conductivity: An Alternative Method for the Measurement of Soil Compaction.

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Abstract
Four treatments of tillage were compared by measuring soil thermal conductivity. Bulk density and difference between treatments pointed to the discriminatory capacity of the method. The soil thermal conductivity measure or Electrothermal Method (EM) has demonstrated to be a new and reliable indicator for the compaction state of soil.

Keywords: thermal conductivity, tillage, soil compaction, soybean, cocoa

1 Introduction

The development of appropriated tillage systems requires knowledge of mechanisms that influence compaction changes in the different tropical soils. A tillage treatment is defined by the use of different heavy machineries to prepare the land for different cultivation uses. However, the intensive use of heavy machinery has involved soil compaction problems (i.e. volume reduction of soil pores), and production decrease of different crops up to 40%. As example, we have the sugarcane cultivation in the Departamento del Valle del Cauca, Colombia (Rodríguez, 1996; Torres, 1995). Very few experiments have studied the effects of tillage methods on soil compaction or yield in tropical crops (Swanton *et al.*, 1999; Brandt, 1992). There are a multitude of factors affecting soil compaction, and evaluation of these factors is important to our understanding. Therefore, a study was initiated to determine the efficient of thermal conductivity to measure impacts of tillage systems on soil compaction.

2 Soil thermal conductivity

One of the most important processes of heat transport in soil under normal conditions is conduction. Conduction refers to the transport of heat by molecular collisions. For a soil, the heat flow equation is given by:

$$D_T \nabla^2 T - \frac{\partial T}{\partial t} + r_H = 0 \quad (1)$$

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where $D_T = \lambda / C_{soil}$ is the soil thermal diffusivity, T is temperature, t is the time, C_{soil} is the soil volumetric heat capacity (assuming C_{soil} constant), r_H is a source or sink of heat, and λ is a constant called soil thermal conductivity (Porta *et al.*, 1994).

3 Measurement of soil thermal conductivity

The Electrothermal Method is strictly a laboratory technique and can be used in situ. The method uses a cylinder (5×5 cm), which is wrapped by a thin metal wire that is heated electrically to serve as the heat source and a thermocouple to measure the temperature rise. The thermocouple is placed inside the cylindrical tube, which is inserted into the soil. When the wire is connected to a continuous current, the wire heats up causing heat to flow radially. Due to cylindrical symmetry Eq. (1) must be expressed in cylindrical coordinates

$$D_t \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) - \frac{\partial T}{\partial t} = -\frac{T_0}{D_T} \tag{2}$$

With the boundary and initial conditions:

$$\left. \frac{\partial T}{\partial r} \right|_{r=a} = qT \quad ; \quad T_{(r=a)} = T_0$$

The steady-state is obtained by Laplace Transform method:

$$T = T_0 + \frac{q}{4\pi\lambda} \ln \tau \tag{3}$$

Where T_0 is the temperature at time t_0, q (ΔVIt, ΔV: voltage, I: electrical current) is the heat flowing per unit time and unit length of wire, and τ is a parameter related to time t. A graph of T as a function of $\ln \tau$ is a straight line whose slope is proportional to the inverse of soil thermal conductivity (λ) (Buchan, 1991; Carslaw and Jaeger, 1959).

4 Experimental design

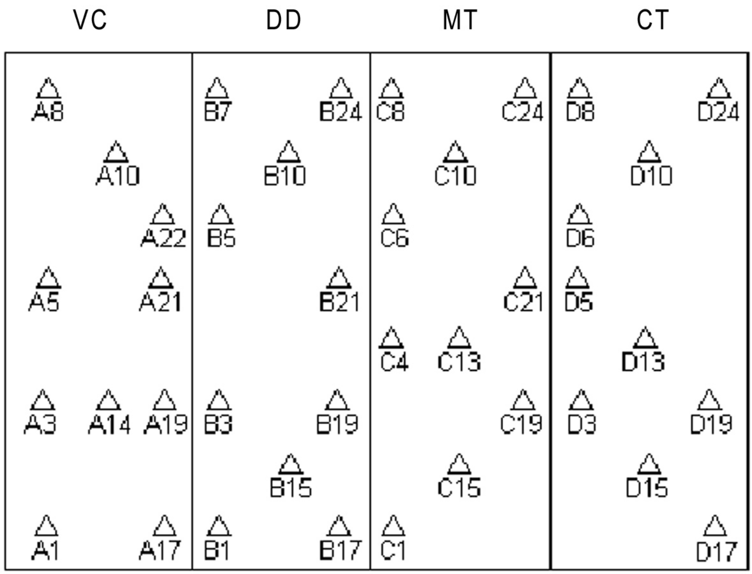
The investigation was carried out on a soybean field (Lote Number 14), at the research station of CORPOICA, Palmira (Colombia). The investigation area was 3,5 ha divided in four blocks (54 m-wide and 170 m-long). Each treatment belongs to a block. The possible relationship between thermal conductivity and soil compaction was measured on the following four treatments: Vibratory Chisel (VC), Conventional Tillage (CT), Direct Drilling (DD) and Mulch Tiller (MT).

The results were compared with a cocoa field (Lote Number 30, 2,35 ha), which was left without tillage for more than 30 years. The purpose of the cocoa field is to have a reference pattern to the variation of the physical properties such as to relate them with the different soil compaction treatments (Reyes and Viera, 2001; Ruiz, 1999). The distribution of the field design is presented in the figure 1.

5 Results and Discussions

Measurements were taken at two depth levels: h_1 from 0 cm to 10 cm and h_2 from 10 cm to 20 cm. Since the traditional measurement to evaluate the soil compaction grade

Figure 1: Distribution of the field design.



is given by bulk density (ρ_a), therefore this parameter was measured in order to relate it with the soil thermal conductivity (λ). Figure 2 shows the characteristic curve the heat flow for Conventional Tillage treatment.

Table 1 shows mean values for each physical properties evaluated and the corresponding significant difference. From this table we can see that there are two groups conformed in this way: Group 1, VC- and CT-treatments, and Group 2, DD- and MT-treatments have highly significant difference of soil thermal conductivity λ. However, for bulk density there is no difference; therefore you cannot efficiently infer state of soil compaction using these parameter.

By comparing the results of bulk density and soil thermal conductivity the four treatments can be divided in two groups (Table 2): Group 1, representing VC and CT; Group 2, conformed by DD and MT. For bulk density, a 2,5%-significance was obtained for h_1, and 0,5%-significance for h_2. For thermal conductivity, a 0,1%-significance was obtained; this shows that the electrothermal technique can differ statistically, with high significance (Reyes, 1980) the two groups among the studied treatments.

Table 2 shows values of soil thermal conductivity and bulk density among the treatments, to the two evaluated depths.

According to these results, soil thermal conductivity provides highly significant information for determining the degree of soil compaction. There is a high probability that the differences between treatments are highly statistically significant. This could be due to

Table 1: Values for soil thermal conductivity λ and bulk density ρ_a for four treatment of tillage and reference pattern and statistical variance analysis of λ and ρ_a for all treatments.

Treatments	*Soil depth h_1*		*Soil depth h_2*	
	thermal conductivity $\lambda\ \left(\frac{Cal}{cm\ s\ ^\circ C}\right)$	*bulk density* $\rho\ \left(\frac{g}{cm}\right)$	*thermal conductivity* $\lambda\ \left(\frac{Cal}{cm\ s\ ^\circ C}\right)$	*bulk density* $\rho\ \left(\frac{g}{cm}\right)$
VC	0,85 a	1,53 ab	0,83 a	1,61 ab
DD	1,03 b	1,68 c	0,99 b	1,70 c
MT	1,05 b	1,56 b	1,04 b	1,67 bc
CT	0,87 a	1,55 ab	0,86 a	1,65 bc
cocoa	1,18 c	1,45 a	1,06 b	1,56 a
LSD	0,09 (1%)	0,11 (1%)	0,09 (1%)	0,05 (5%)

* LSD: Least significant difference.

Values with same letter in each column do not differ significantly.

Figure 2: Characteristic curve of temperature as function of logarithm of τ for the Conventional Tillage treatment.

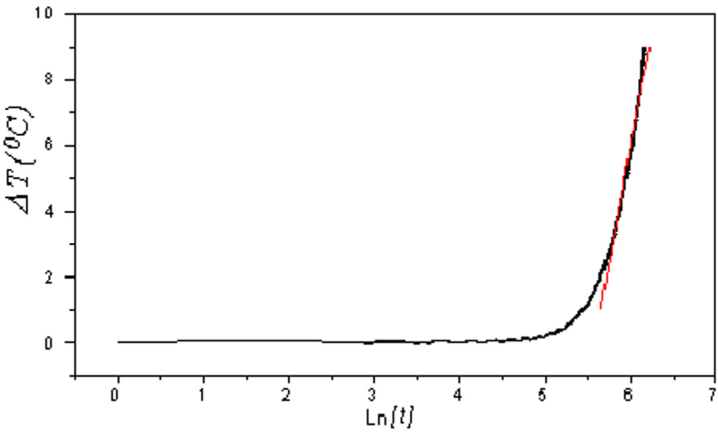


Table 2: Statistical values by means of t-Student test between treatments for thermal conductivity λ and bulk density ρ_a.

Comparisons	*thermal conductivity (λ)*		*bulk density (ρ_a)*	
	h_1	h_2	h_1	h_2
VC vs. CT	NS	NS	NS	NS
VC vs. MT	NS	S (5,0%)	HS (0,1%)	HS (0,1%)
VC vs. DD	HS (0,1%)	HS (0,1%)	HS (0,1%)	HS (0,1%)
DD vs MT	HS (0,1%)	NS	NS	NS
DD vs CT.	HS (0,1%)	S (0,5%)	HS (0,1%)	HS (0,1%)
MT vs CT	NS	NS	HS (0,1%)	HS (0,1%)
VC-CT vs DD-MT	S (2,5%)	HS (5,0%)	HS (0,1%)	HS (0,1%)

NS: no significance, S: significance, HS: high significance.

the fact that heat conductivity is controlled by all three phases (solid/liquid/gas) of the soil.

Lastly, figure 3 shows a zonification for h_1 and figure 4 for h_2, comparing the results of thermal conductivity and soil bulk density; it can be seen that thermal conductivity shows greater significant difference between the four treatments.

6 Conclusions

The dependence of soil thermal conductivity on all three phases that compose soil, is an advantage, in that it is affected by properties of the whole soil. As all three phases affect thermal conductivity, both static and dynamic soil properties are reflected in heat conduction measurements.

The Vibratory Chisel treatment presented lowest values of λ because better structural conditions are found in this treatment, involving lowest values of ρ_a all together. This situation coincides with the lowest packing grade between soil solid particles and thus betters aeration conditions decreasing consequently the heat conduction in soils.

Mean values of soil thermal conductivity for Direct Drilling treatment are high because of the lack of tillage which increases compaction. At the same time, the morphological structure shape of the soil remains undisturbed, thus preserving many micropores. In this case, heat conduction is high as is the contact area between soil particles, involving compaction problems.

The Mulch Tillage treatment presents an improvement in soil physical properties within the first 10 cm-depth; this is a consequence of progressive incorporation of crop residuals.

Figure 3: Spatial distribution to the four tillage treatments by means values of soil thermal conductivity and bulk density to h_1.

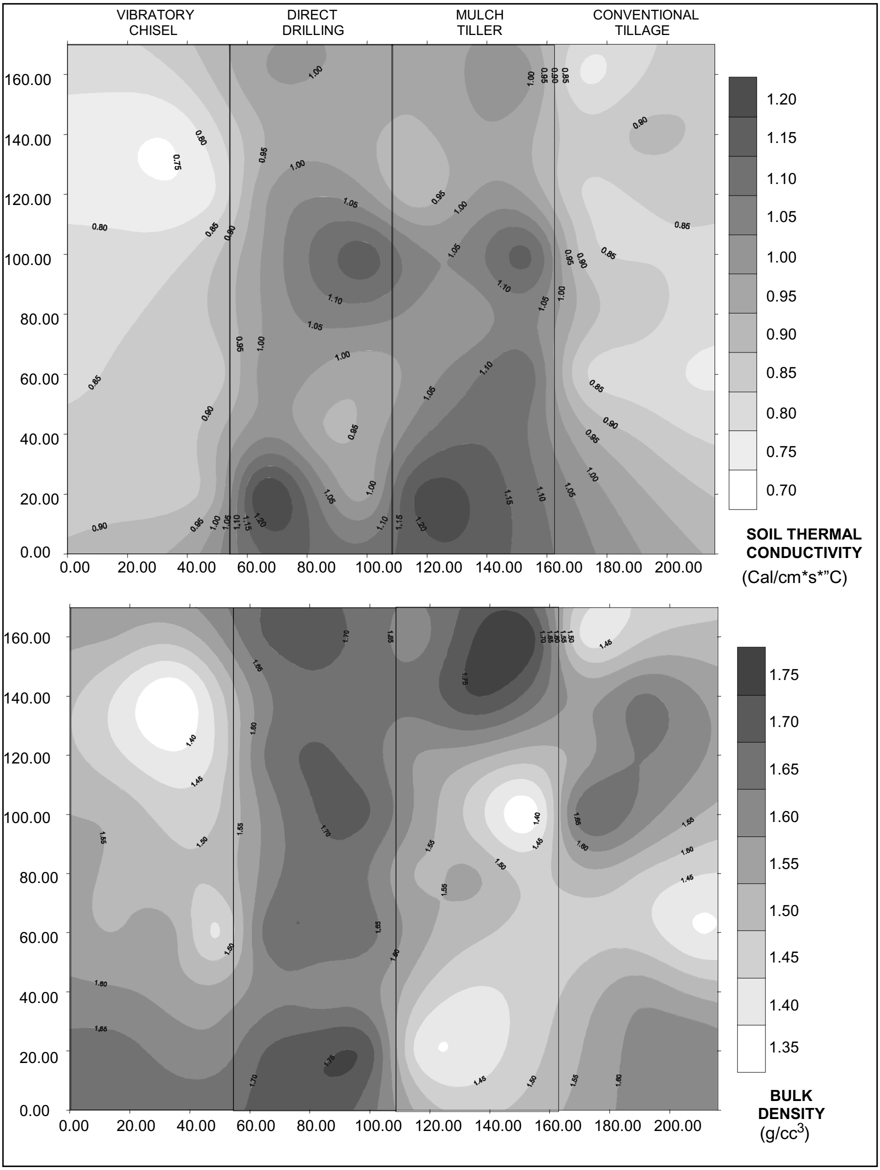
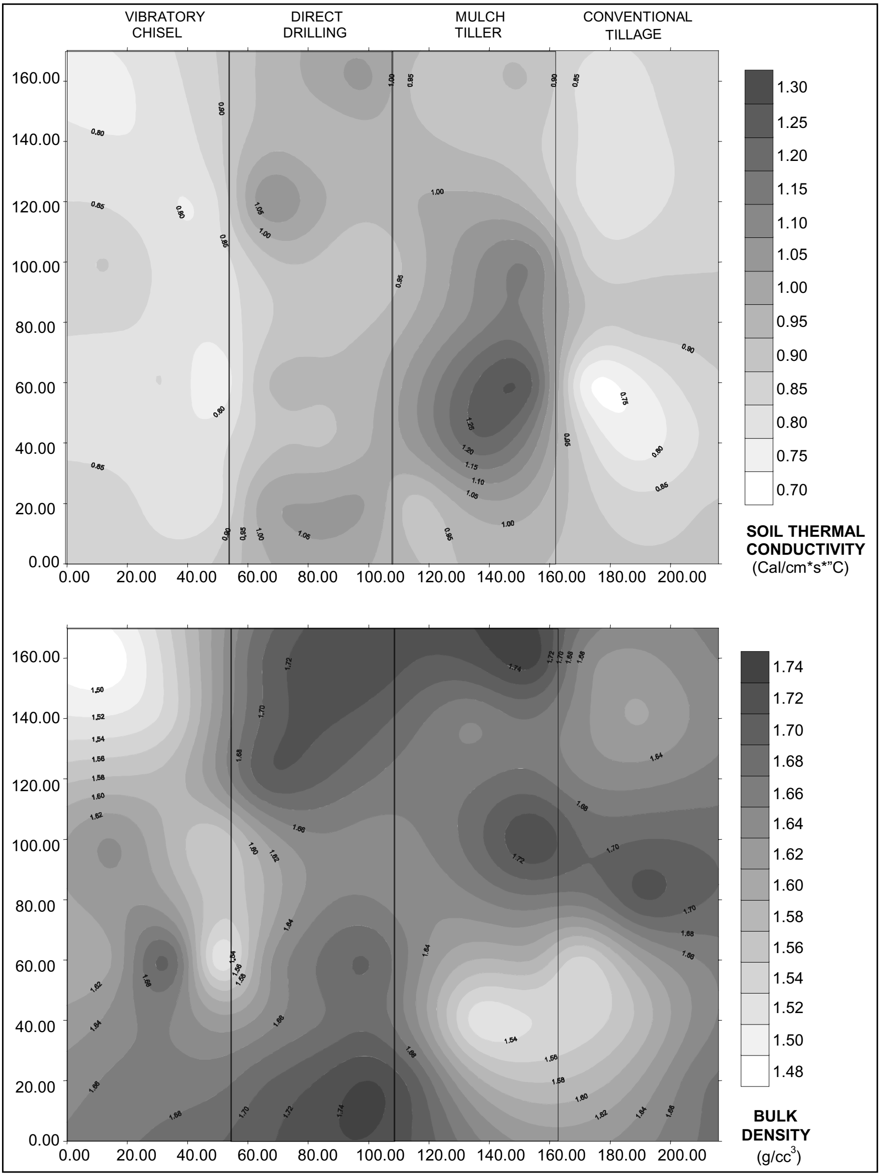


Figure 4: Spatial distribution to the four tillage treatments by means values of soil thermal conductivity and bulk density to h_2.



The thermal conductivity evaluations carried out in Conventional Tillage treatment, showed an increase of conductivity in comparison to VC treatment. This shows that CT degrades soil physical properties, as shown by the variability of the bulk density values for this treatment. However the most stable values of the thermal conductivity for this treatment show that it is a better indicator of soil physical degradation.

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