Method of evaluation of ground compaction by means of a TDR probe connected to a soil penetrometer

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Abstract: Construction and development of cities imposes profound modifications on the environment, such as: destruction of forests, reduction of water infiltration, increase of the pluvial water concentration, pollution, etc. These impacts are more intense and serious in developing countries, because the construction/development is made, normally, without planning and considering the limitations of the environment. Around the cities the problems are more serious because the urban infrastructure is deficient, and this causes the expansion of problems into other areas of the hydrographic basin. The occupation of upstream catchment areas of cities, without adequate planning causes serious problems for the city, such as erosion, siltation, flooding etc. An important factor to be considered is the change in the natural condition of compaction of the soil that, as a consequence, can change infiltration and runoff rates, which may result in more erosion, flooding and siltation. In this paper an efficient, fast and innovative method is presented to evaluate the degree of compaction of soils using a TDR probe connected to a penetrometer for soil assessment. It is known that the resistance to penetration depends on the physical characteristics of the ground, to its state of compaction and its moisture content. This equipment makes it possible to infer realistic values of the degree of compaction of the soil in terms of absolute values of resistance by means of simultaneous measurement of resistance to penetration and moisture content. An example of application of this method in a hydrographic basin located in the southeast region of Brazil is presented in the paper. The results showed that the method is efficient in evaluating the characteristics of current compaction of the soils and it can also be used to verify changes of compaction caused by different activities developed in the same soil.

Résumé: Le processus de construction et/ou développement de villes impose des modifications profondes sur l'environnement comme: destruction de forêts, réduction des eaux d'infiltration, augmentation de concentration des eaux pluvielles, pollution, etc.Ces impacts sont plus intenses et sérieux dans des pays en développement parce que la construction/développment sont faits, en général, sans aucun plan ou considération des limitations de l'environnement.

Autour des villes les problèmes sont plus sérieux parce que l'infrastructure urbaine est déficente, ce que provoque l'expansion des problèmes pour les autres aréas du bassin hydrographique. L'occupation des aréas de captation des eaux des villes sans un plan propre cause des problèmes sérieux pour la ville, elle même, comme l'érosion, la siltation, les inondations, parmi d'autres. Un facteur important qui doit être consideré est le changement des conditions de consolidation du sol que, par conséquent, peut changer les taxes d'infiltration et de "run-off", ce que résulte en plus d'érosion, inondation et siltation. Dans cette étude est présentée une méthode éfficace, rapide et innovatrice pour évaluer le degré de compactation des sols à travers l'utilisation d'une sonde TDR connectée à un pénétromètre pour sols. Il est connu que la résistence à la pénétration depend des caractéristiques physiques du sol, son état de compactation et son contenu en humidité.Cet équipement permet d'inférer des valeurs réalistiques pour le degré de compactation du sol par des valeurs absolues de résistence à travers la mésure simultanée de la résistence à la pénétration ainsi que du contenu en humidité. Un exemple de l'application de cette méthode dans un bassin hydrographique localisé dans la région sud-est du Brésil est presenté en cette étude. Les résultats ont montré que la méthode est éfficace dans l'évaluation des caractéristiques de compactation courrantes des sols et peut aussi être utilisée pour vérifier les modifications de compactation provoquées par des différentes activités developpées sur le même sol.

Keywords: in situ tests, land use, environmental impact, monitoring.

INTRODUCTION

The compactation process modifies the natural physical structure of soil, which also modifies the chemical, and biological conditions (Bertoni & Lombardi Neto, 1990). Quantifying the ground compaction has high relevance, because it has a direct relationship with the runoff rate and water infiltration. Soils with high compaction present an arrangement of their elementary particles that hinders the water infiltration, increases the superficial water flow, and favours the erosion process of the superficial soil layer, as well as bringing about a reduction of the productivity potential of the earth (Bertoni & Lombardi Neto, 1990). Any modification of the natural conditions of land use, such as the removal of natural forest covering, tends to alter the primary conditions of ground compactation and modify the natural ground state.

A way to quantify these alterations is made by use of environmental attributes and/or processes of the environment, as indicators of those modifications. These attributes and/or processes are termed Geoindicadores (ITC, 1996; COGEOENVIROMENT, 1992). The geoindicadores represent a set of tools that help the understanding of environmental impacts and risks associated with active processes in the environment. They help in the management of the ecosystem and have great application in integrated environmental monitoring. COGEOENVIROMENT (1992) proposed twenty-seven indicators, internationally identified and defined as able to be used in management and evaluation of environment modifications, of natural origin or induced by human activities. However, not all the geoindicadores have wide application, because in some peculiar environmental conditions, the establishment of new attributes is required to be used as indicators of environmental modifications.

This paper presents a methodology that uses ground compactation as an environmental indicator of modifications caused by different land use activities and occupation. Penetration resistance measurement by a combined impact penetrometer –TDR moisture probe can be used as an alteration indicator. This probe was developed by Vaz et al. (2001).

PENETRATION RESISTANCE – PENETROMETER-TDR PROBE

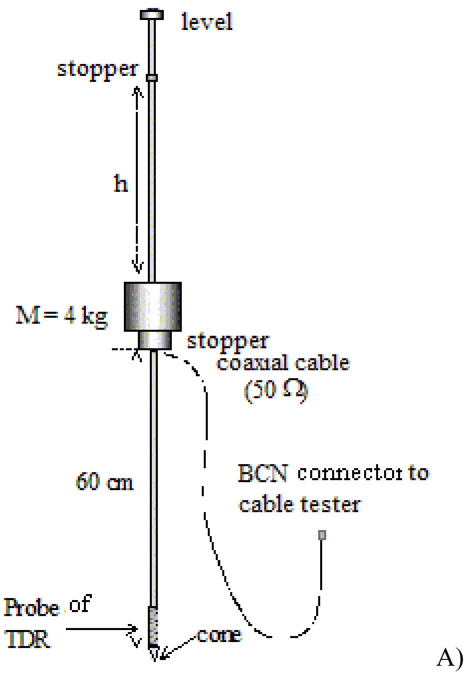
The most common way to determine the state of ground compaction is by using a soil penetrometer. The penetration resistance (PR) can be interpreted as the necessary pressure to insert a cone of standard size into the soil (Bradford, 1986). The cone insertion into the ground can be made in two ways, firstly, the operator forces the penetrometer against the soil or, secondly, the penetrometer is inserted through impacts produced by the fall of a fixed weight (Stolf et al., 1983). The second method allows the PR to be inferred by the relationship between the number of impacts and the depth of penetration. The determination of PR is accomplished by the number of total blows executed (TN) to penetrate a fixed depth value. The TN provides the PR behaviour and verifies the state of ground compaction for different land use activities by comparison of measurements. The TN value is calculated by the equation below:

$$TN = BN/X \tag{1}$$

where TN is the penetration resistance index (number of blows /depth), BN is the total blows number executed and X is the depth profile (in 60 cm intervals)

Vaz & Hopmans (2001), noted that the ground PR can vary significantly across an area due, in particular to soil moisture (θ) and bulk density (ρ). These parameters must be taken into account to obtain correct evaluation in terms of absolute PR values.

For simultaneous measurement of these parameters and PR, an impact penetrometer was used (I model IAA/Planalsucar - Stolf) combined with a TDR- moisture probe. The probe has a helical geometry and is located at the base of the penetrometer, immediately above the penetration cone (Figure 1a). The TDR probe consists of two steel wires (conductor and ground), each 26 cm long, wired around a 5 cm long PVC (Kevlar-nylon material) tube, with 2 mm separation distance between the two wires (Vaz & Hopmans, 2001) (Figure 1b).



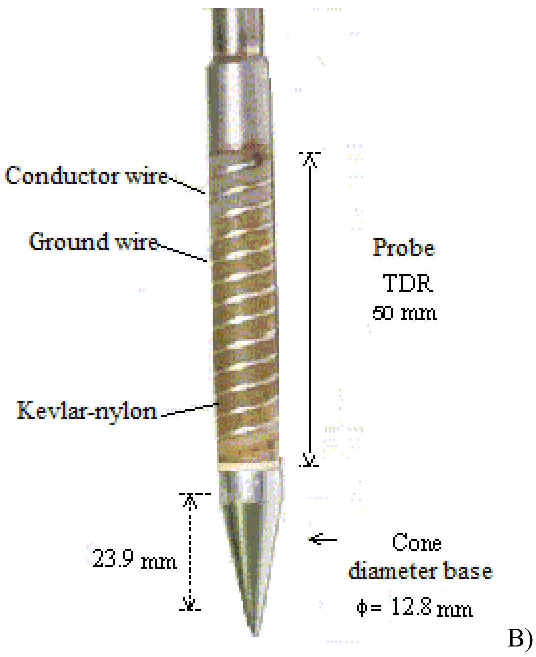


Figure 1. A) Combined penetrometer-TDR moisture probe B) Details of the spiral TDR-moisture probe (VAZ & HOPMANS, 2001).

The principle of time domain reflectometry (TDR) was used to determine soil water content, by using a tester cable (Tektronix 1502B) connected to a penetrometer and a laptop. The water content measurements are processed through the WinTDR 6.0 software, supplied by the Soil Physics Group, Utah University, USA. The penetrometer model used was initially developed for measuring the ground penetration resistance in areas destined for development of agricultural practices.

Time Domain Reflectrometry Theory (TDR)

Time domain reflectometry (TDR) is a soil moisture measurement technique (Topp et al., 1980) that is based on the speed of measurement or travel time of electromagnetic waves along a wave guide of known length inserted into the soil (OR et al., 2001). The travel time measured is proportional to the soil water content because of the increasing changes of the bulk soil dielectric constant, as determined by the following expression:

$$T = L\varepsilon c\ ? \qquad (2)$$

where T (s) is the travel time, L (cm) the length of the wave guide into the soil, ε the dielectric constant of the soil around the wave guide and c (cm^{-1}) the speed of the light.

The soil moisture was estimated by WinTDR 6.0, which provides the soil water content through the universal Topp equation (Topp et al, 1980). The Topp equation is an empirical polynomial equation of degree 3 that establishes the relationship between θ and ε, as presented below:

$$\theta = 5.3x10^{-2} + 2{,}92x10^{-2}\varepsilon_b + 5.5x10^{-4}\varepsilon^2_b + 43.x10^{-6}\varepsilon^3_b \qquad (3)$$

where θ is the soil water content and ε is the dielectric constant of the soil.

FIELD MEASUREMENTS

Prior to the field work, TDR-probe calibration was carried out through laboratory measurement experiments, where the moisture curves for three residual soils in the area were obtained. The first was derived from gneiss interlayered with basic rocks, the second from gneiss interlayered with quartzites and the third from migmatites. As a result, polynomial adjustment coefficients were obtained (Table 1) and then inserted in the WinTDR 6.0 software, in the universal equation of Topp (Eq. 3),

Table 1. Polynomial adjustment coefficients.

Soil texture	a*	b*	c*	d*	r^2
Sandy	-1.1769	0.5602	-0.0762	0.0036	0.968
Argillaceous	-1.2510	0.5367	-0.6023	0.0024	0.905

* **a, b, c, d** – coeffcients adopted to Topp's equation.

A total of 87 field measurements were conducted in six residual soils and five types of land use. The measurements were taken in an area of 1670 km^2 located in the centrale-east portion of São Paulo State, consisting of the Rio do Peixe hydrographic basin.

This basin presents areas that still have natural soil conditions, characterized by the existence of native forest, and areas with different kinds of land use occupation, like coffee, sugar cane, vegetables, corn and bean cultures besides areas of pasture (SILVA, 2005). The soils were drived from porphyritic granites; gneisses interlayered with quartzites (ReGnQ); gneisses interlayered with basic rocks (ReGnB); migmatites (ReMig); ultramylonites (ReUtm) and blastomylonites (ReBtm) (Figure 2, Table 2).

For each investigated point, θ values and TN were obtained. From the 87 measured points, five were not considered in the analysis of the results. Two of these points were discarded due to the loss of the penetrometer-TDR probe caused by roots, and the other three points presented anomalous PR characteristics due to, the rocky fragments present in the investigated profile that provided very high resistance values.

RESULTS

The obtained data were analyzed by soil type, with verification of penetration resistance behaviour versus different land use. Data for each soil type were analyzed according to the land use versus the TBN values and θ average (Figures 3 to 8).

Observance of the graphs above it is possible to verify that in a general way that TBN varies inversely to the average θ of the soil profile, and also varies as function of the different land use. For activities such as pastural and coffee culture, a regular behaviour of TN values distribution was verified. For sugar cane practices and different cultures a larger variability in behaviour was verified. For the best characterization of PR behaviour versus θ average, these parameters were correlated to soil type, considering all of the effective land uses (Table 3). Good correlations were only obtained for the ReUtm and ReBtm soils, where the determination coefficients (R^2) 0.87 and 0.85 were verified, respectively. In other soils the coefficients obtained did not indicate good correlations. A possible cause of the bad correlation could be the influence of the different land use in the PR behaviour. This is well characterized in ReGnB and ReGnQ soils, which present of all types of land use present in the basin area. In these soils the R^2 values are very low, smaller than 0.5.

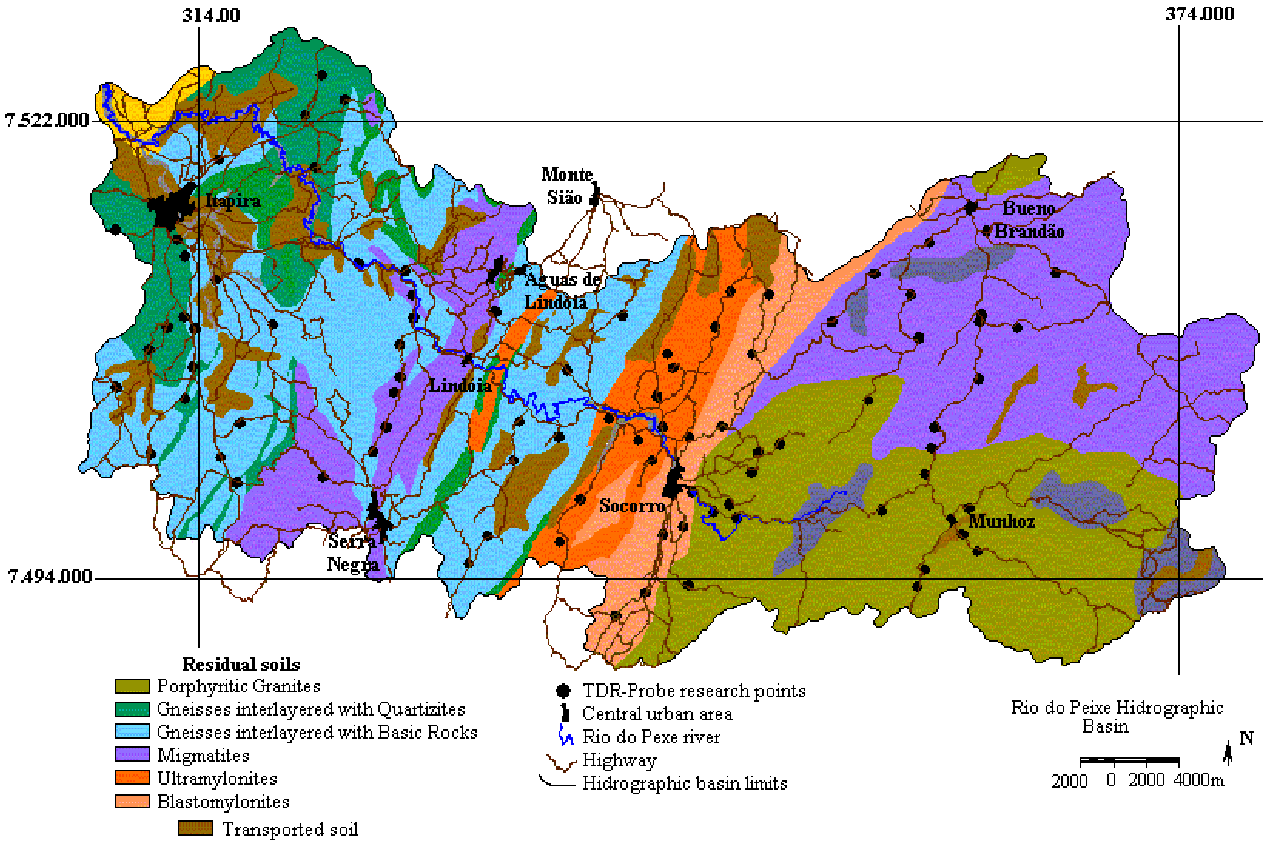


Figure 2. Rio do Peixe Hydrographic Basin. Types of soils and local points of the combined penetrometer-TDR probe measurements.

Table 2. Soils characteristics (SILVA, 2005).

Soil	Characteristics
ReGrp	Texture - (Coarse Sand – 11-18%, Fine Sand – 30-48%, Silt -15-28%, Clay -12-36%). ρs – 2.58-2.36(g/cm^3). ρdfield 1.19-1.42 (g/cm^3), n 45-54%; e_0 0.84-1,20.
ReGnB	Texture - (Coarse Sand – 6-15%, Fine Sand – 10-52%, Silt -11-48%, Clay -8-63%); ρs – 2.65-2.78(g/cm^3); ρdfield 1.51-2.04 (g/cm^3); n 46-52%; e_0 0.96-1.41.
ReGnQ	Texture - (Coarse Sand – 12-60%, Fine Sand – 42-49%, Silt -10-14%, Clay -25-32%); ρs – 2.52-2.91(g/cm^3); ρdfield 1.09-1.58 (g/cm^3); n 46-52%, e_0 0.87-1.0.
ReMig	Texture - (Coarse Sand – 8-16%, Fine Sand – 13-44%, Silt -7-54%, Clay -12-58%); ρs – 2.56-2.78(g/cm^3); ρdfield 1.15-1.22 (g/cm^3); n 41-55%; e_0 0.69-1.24.
ReUtm	Texture - (Coarse Sand – 18-25%, Fine Sand – 34-64%, Silt -28-50%, Clay -0.8-18%); ρs – 2.62-2.76(g/cm^3); ρdfield 1.06-1.24 (g/cm^3); n 44-47%; e_0 0.74-0.89.
ReBtm	Texture - (Coarse Sand – 10%, Fine Sand – 33-38%, Silt -45-52%, Clay -17-15%). ρs – 2.62-2.76(g/cm^3). ρdfield 1.06-1.24 (g/cm^3), n 43-46%; e_0 0.73-0.86.

ρs - specific mass of the solids; e0 – void index, n - natural porosity, ρd - specific mass drought

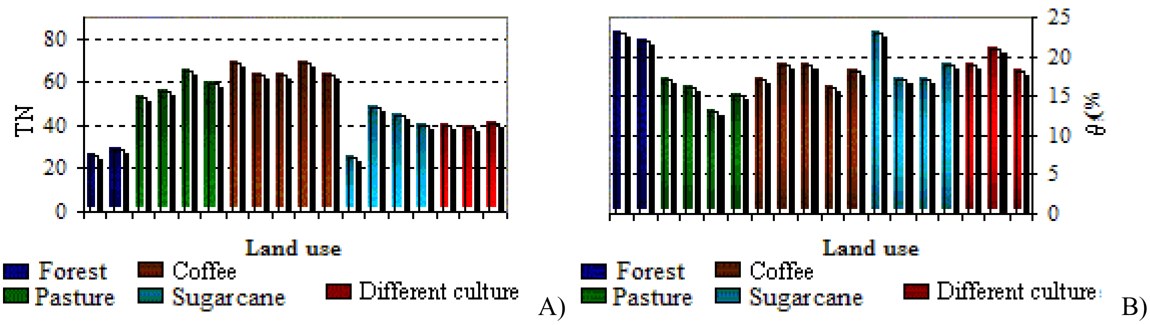


Figure 3. Porphyritic granite residual soils (ReGrP). A) TN X land use occupation. B) θ average X land use occupation.

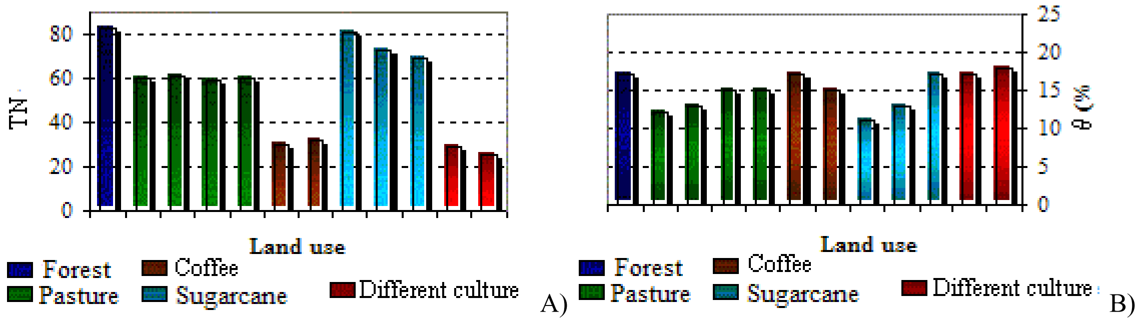


Figure 4. Gneisses interlayered with basic rocks residual soils (ReGnB). A) TN X land use occupation. B) θ average X land use occupation.

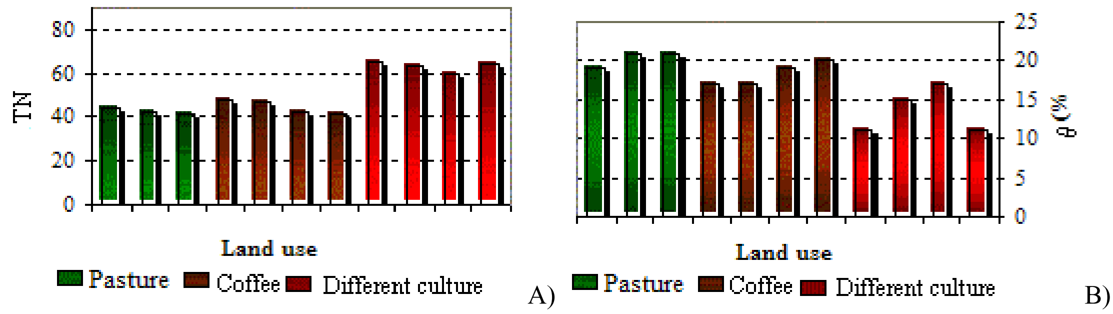


Figure 5. Gneisses interlayered with quartzites residual soils (ReGnQ). A) TN X land use occupation. B) θ average X land use occupation.

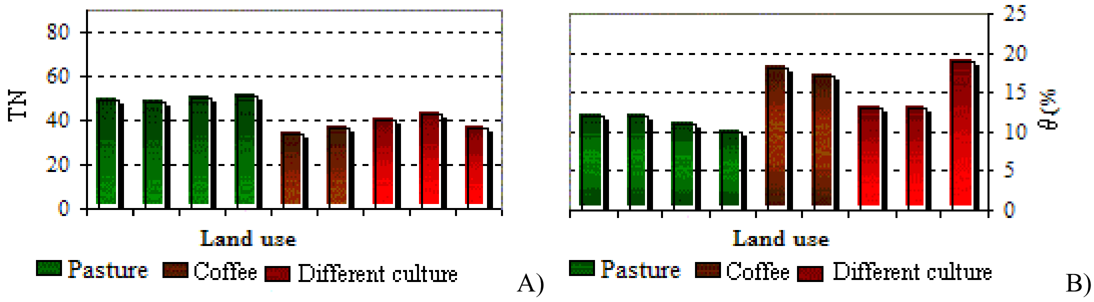


Figure 6. Migmatites residual soils (ReMig). A) TN X land use occupation. B) θ average X land use occupation.

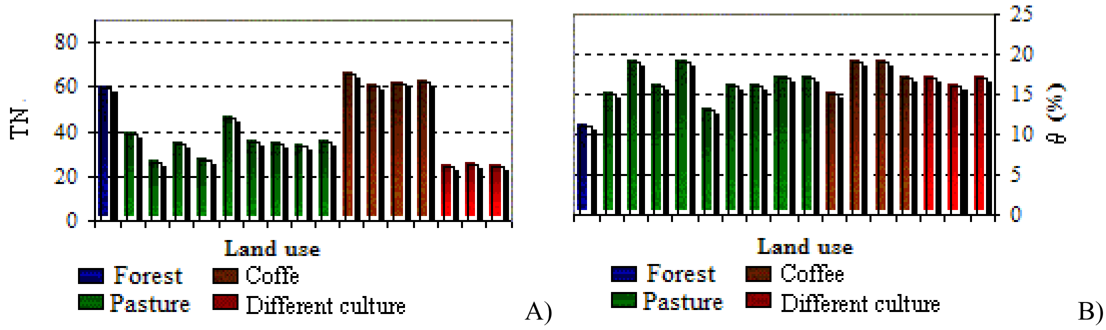


Figure 7. Ultramylonites residual soils (ReUtm). A) TN X land use occupation. B) θ average X land use occupation.

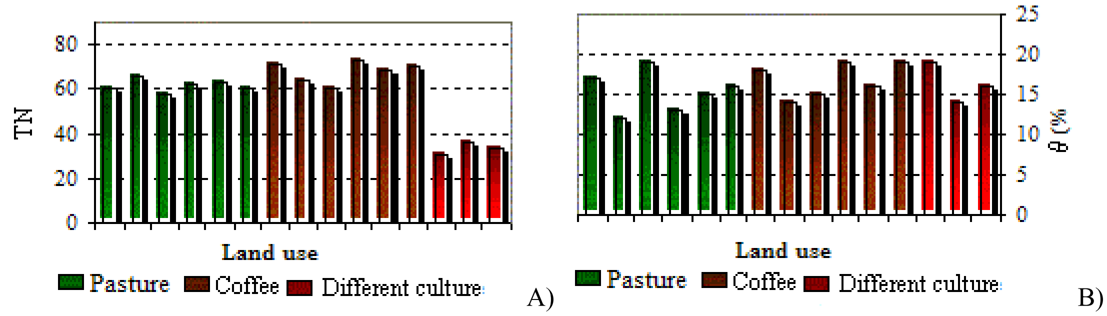


Figure 8. Blastomylonites residual soils (ReBtm). A) TN X land use occupation. B) θ average X land use occupation.

Table 3. R^2 values used to establish the relationship between TN and θ average.

Soils	**R^2Value.**
ReGrp	0.05
ReGnB	0.45
ReGnQ	0.22
ReMig	0.002
ReUtm	0.82
ReBtm	0.87

To verify the influence of the different land use in the TBN behaviour against θ average, for each soil type these parameters (R^2) were calculated for each land use. In the cases of practices with registration below three measured points, as native forest in the ReGnB, ReGnQ and ReMig; and coffee in ReGnQ, the R^2 were obtained by combining data from different practices, as natural forest x different cultures, and pasture x coffee (Table 4).

Table 4. R^2 TN values X θ for each type of land use occupation.

Soil	**Land use occupation**	**N° of research points**	**. R^2**	**R^2 Equations**
ReGnB	Natural forest/Different cultures	4	0.81	TNB = -3.7143*(θ)+112.43
	Pasture	4	1	TNB = -3*(θ)+104
	Coffee	5	0.82	TNB = -2.2941*(θ)+106.24
	Sugarcane	3	0.98	TNB = -3.5833*(θ)+107.42
ReGrP	Pasture	6	0.90	TNB = -1.017*(θ)+78.57
	Coffee	6	0.87	TNB = -1.8636*(θ)+98.73
	Different cultures	3	0.95	TNB = -0.9737*(θ)+49.24
ReGnQ	Natural forest/Different cultures	3	0.30	TNB = -31*(θ)+583
	Pasture/Coffee	6	0.48	TNB = -5.9032*(θ)+135.76
	Sugarcane	3	0.94	TNB = -3.2308*(θ)+118.85
ReMig	Natural forest/Different cultures	9	0.98	TNB = -5.9798*(θ)+124.19
	Pasture	5	0.95	TNB = -3.0945*(θ)+85.22
	Coffee	5	0.92	TNB = -1.3182*(θ)+85.32
ReUtm	Pasture	3	0.89	TNB = -1.25*(θ)+67.75
	Coffee	4	0.96	TNB = -2.2963*(θ)+86.407
	Different cultures	4	0.85	TNB = -0.6667*(θ)+72
ReBtm	Pasture/Coffee	5	0.99	TNB = -2.381*(θ)+76.733
	Different culture	3	0.81	TNB = -0.9167*(θ)+53.47

The coefficients showed that all of the soils, with the exception of ReGnQ soil, had good results of correlation between TN and θ averages. This confirms the influence of land use in PR behaviour. Another analysis was carried out to verify which land use, among those regularly covering the ReGnB, ReMig, ReUtm and ReBtm soils, were responsible for the highest values of PR. The analyzed practices were coffee culture, different cultures and pasture.

To characterize the PR behaviour without the θ variability, four fixed θ were established. The θ values correspond to the maxima, minima and median contents registered in the points concerned (Table 5). In the cases where the TN values for these θ were not obtained by direct investigation, they were calculated through the correlation equations obtained (Table 4).

Table 5. Correlation values TN X θ for each soil type and land use occupation.

Soil /Land use occupation	**θ 11%**	**θ 15%**	**θ 19%**	**θ 21%**
	TBN	**TBN**	**TBN**	**TBN**
ReGnB - Pasture	71	59	47	41
ReGnB - Coffee	81.0	71.8	62.7	58.1
ReGnB - Different Cultures	71.6	56.7	41.9	34.4
ReGrP - Pasture	67.6	63.5	59.4	57.4
ReGrP - Coffee	78.2	70.8	63.3	59.6
ReGrP - Different Cultures	38.5	34.6	30.7	28.7
ReMig - Pasture	70.8	65.5	60.3	57.6
ReMig - Coffee	38.5	34.6	30.7	28.8
ReMig - Different Cultures	58.4	34.5	10.6	-1.4
ReUtm - Pasture	54	49	44	41.5
ReUtm - Coffee	61.1	52.0	42.8	38.2
ReUtm - Diferent Cultures	64.7	62.0	59.3	58.0
ReBtm - Pasture/Coffee	51	41	31	22
RebBtrm - Different Cultures	43	40	36	34

For ReGnb soil it was verified that the coffee culture is responsible for the highest values of PR (Figure 9). In these cases, pastural activities and different cultures were responsible for the lowest resistance values of PR. Similar behaviour was observed in the ReGrP soils (Figure 10).

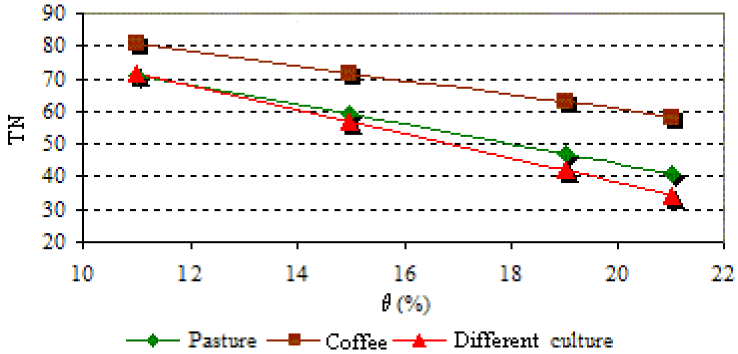


Figure 9. PR for pasture practices, coffee and different cultures in the ReGnB soils.

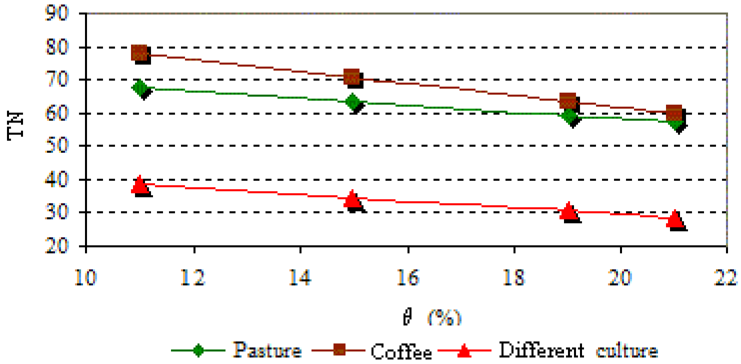


Figure 10. PR for pasture practices, coffee and different cultures in the ReGrP soils.

In ReMig soils, pasture practice produced the highest resistance values. In these soils, the activities of different cultures and coffee presented a variable resistance according to the θ average. For low θ values, the coffee culture was responsible for the lowest PR values. Nevertheless, for θ values higher than 20% in areas with different cultures, the PR became almost nill (Figure 11).

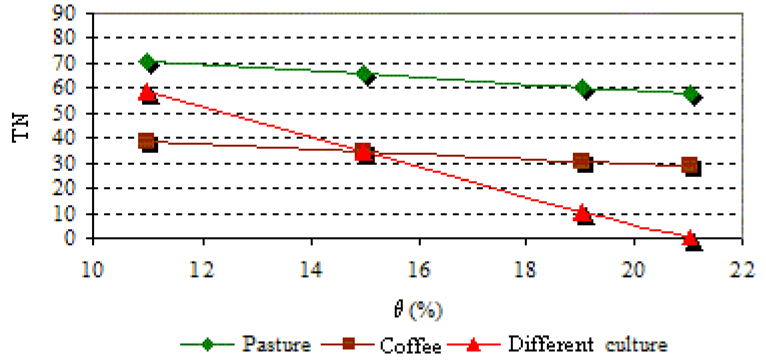


Figure11. PR for pasture practices, coffee and different cultures in the ReMig soils.

ReUtm soil exhibited similar behaviour to the ReMig soil, differing for the practice of different cultures that stand out as the main ones responsible for the highest PR values (Figure 12).

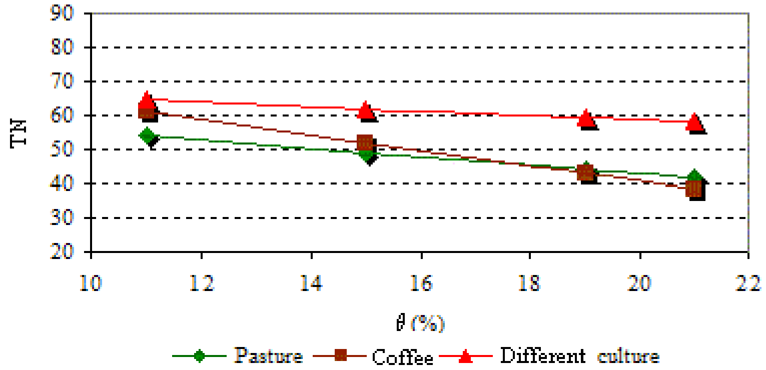


Figure 12. PR for pasture practices, coffee and different cultures in the ReUtm soils.

In ReBtm soil the highest and lowest PR were determined according to the variation of θ. For low θ, the pastural activities and coffee culture were responsible for the highest PR values, and for high θ the opposite was the case, where the different cultural activity had the higher PR values (Figure 13).

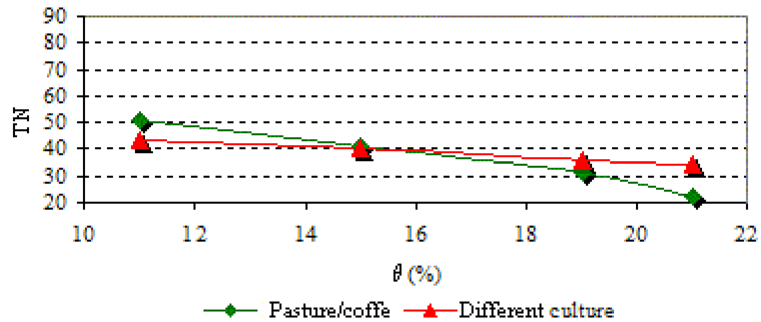


Figure 13. PR for pasture practices, coffee and different cultures in the ReBtm soils.

CONCLUSIONS

The use of ground compaction measurements by the combined penetrometer-TDR probe was shown to be an efficient indicator of environmental modifications. Measurements indicative of the PR along with soil water content, allow the characterization of modifications in the behaviour of PR, caused by different land use.

In the example here presented, it was verified that, in a general way, the average θ is a parameter that characterized the highest influence in PR behaviour. The more detailed analysis with evaluation of PR behaviour for fixed θ values showed that the activities of coffee culture and pastural practices are responsible for the highest PR values for three of the five analyzed soils, that allows them to be characterized as the classes of land use responsible for the highest alterations in the PR behaviour for the soils in the Rio do Peixe hydrographic basin. The highest PR values found in coffee culture and pastural activities can be assigned to the fact that these soils undergo little change in activity compared with the soil in the practices of different cultures.

The establishment of PR standard curves against θ for each soil in the basin, and for each land use, permitted a behaviour characterization that will be used in the future analyses of changes in the characteristics of these soils. This aspect allows the conclusion to be drawn that the proposed index, even in preliminary character, can be considered as an indicator of environmental changes, according to the concept of COGEOENVIROMENT (1992).

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