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Eveluation of the Quality of the Soil From Soil Physical-Hydrical Indicators

Paulo Leonel Libardi and Flávia Carvalho Silva

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1. Introduction

Due to the high demand for food, farmers have intensified agriculture seeking high productions. Hence, agriculture, amongst other activities, has been considered a highly potentially polluting activity of all the system water-soil-plant-environment. As a consequence, the intensive use of the soil causes its degradation. The accelerated waste will always exist if the farmer does not take proper measures to combat the causes related to various processes such as: chemical depleting and leaching, erosion, physical and biological degradation. The growing concern about the environment raised the concern about the quality of the soil. Ever since, several concepts of soil quality have been proposed, however, currently "soil quality" is defined as the capacity of the soil to keep biological productivity, environment quality and the vegetal and animal lives healthy on earth [1]. There has currently been a wide discussion towards environmental patterns and indicators, specially in Brazil, where there are very few studies and even a lack of systematization over the subject, since there is plenty of data that could provide support for an extensive discussion over the topic. The evaluation of the quality of the soil could be carried out by the monitoring of its features or physical, chemical and biological characteristics. In this approach, the expression "soil quality indicators" is being used, since it is the parameter or reference that best translate the conditions of a specific environment compartment. Among them, some attributes or physical indicators that might go through a few medium term changes have been recommended, such as density, porosity, aggregation and compression state. Hydrical conductivity, water retention, storage and density of water flow in the soil may also be indicators of great importance to assess the quality of the soil. Although such parameters are not frequently studied in Brazil, in foreign literature they are reported to vary according to different soil preparations and management. Detailed familiarity of the water dynamics during the development of a culture provides essential elements for the stablishment or improvement of agricultural management practices that aim

to optimize the productivity. Water is a fundamental factor in the development of a culture, interfering mainly in the development of the root system and the absortion and tranference of nutrients for the plants. When a certain culture is irrigated, or when it rains, the water penetrates the soil and redistributes in its interior. If the quantity added by these processes exceeds the soil infiltration capacity, the excess moves sideways over the soil surface. The theoretical-practical knowledge of the runoff water, infiltration and evapotranspiration, the movement of the water in the interior of the soil profile, the absortion of the water by the plants, the draining, etc, is extremely relevant to obtain an increase in the productivity of the cultivars and to prevent the environmental degradation.

2. Body

When hydrical conductivity of a soil in mentioned, it is implicit that a sample of soil is being considered a porous media and as a fluid that moves in it an aqueous solution (hydrical). The methods of direct determination of hydrical conductivity of the soil may be classified in laboratory methods and field methods. In the laboratory methods, samples may be used with deformed structure or samples with undeformed structure and they are subdivided for saturated and unsaturated conditions. For the measurement of the hydrical conductivity of saturated samples a simple equipament is used, denominated permeameter, and for unsaturated samples the hydrical conductivity may be measured under the steady-state condition, in which big or small columns are used and also under transient conditions. The measurement of hydrical conductivity in the field may also be carried out under the saturation condition (below the groundwater) and under unsaturated conditions (above the groundwater). The Instantaneous Profile Method [2]; [3]; [4] is the most commonly used in the field and it is applied for unsaturated conditions in situations in which the groundwater is nonexistent or very deep; it also has the advantage of being possibly used in heterogenous soil [3]. To apply this method in the field, a portion of sufficiently large area of soil must be chosen, so that the processes in the center are not affected by the boundaries. This area must be conveniently instrumented for the measurement of the amount of water in the soil and the matric potential, along the profile until the depth of interest. The surface of the soil is, then, mantained under water depth, in a way that the profile, until de depth of interest is as humid as possible. Reaching this condition, which may be perceived by the virtually no variation of the content of water and the matric potencial with the infiltration time along the profile, infiltration is interrupted and the surface of the soil is covered with a plastic cover to avoid evaporation and the water inlet through the surface. The water in the profile redistributes, then, by the process of internal drainage, and as this process occurs, periodical measurements of water and matric potencial are carried out, data to determine the hydric conductivity K according to the water content θ, that is, the function $K(\theta)$ [5]. The measurements of the water content for this purpose have normally been carried out through a) techinque of neutron moderation or, simply, neutron probe (for example [6], b) tensiometers, installed in several depths, together with their respective retention curves [7] and, more recently, c) time-domain reflectometry technique or, simply TDR [8]. Other techniques are or will be able to be utilized, however, for the measurement of the water content, since the thermogavimetric method, taken as a pattern, the gamma

radiation attenuation techinque and new techniques that have been developed as the computerized tomography (CT), Magnetic Resonance Imaging (MRI), electromagnetic induction, etc. [9]. In Brazil, there are few studies about hydric conductivity for different preparations and soil management and, besides that, the experimental results and contradicting, implicating in detailed analysis of the physical-hydrical properties of the place where the research is being carried out, as this indicator depends on the type of soil, management systems, vegetation, etc. Empirical parameters of K adjustment function θ, allowing function $K(\theta)$ of Oxisol, under different management systems, were obtained by [10] in laboratory. These authors verified discrepancies in the conductivity behavior for different managements and depths, with the same tendency observed in the field determination (Table 1). More recently, [11] observed, in Latosol, that the average hydrical conductivity of saturated soil until 1m deep is larger in bare soil than in cultivated soil (Table 2).

Depth (m)	Woods			Growing upland rice			Irrigated lowland rice		
	a	b	r^2	a	B	r^2	a	b	r^2
0,2	53,47	-22,22	0,85	30,95	-13,78	0,79	59,56	-27,10	0,94
0,3	54,61	-21,61	0,97	48,84	-20,02	0,75	57,76	-27,47	0,95
0,4	54,30	-21,33	0,91	47,26	-18,60	0,94	46,98	-22,05	0,93
0,5	50,86	-20,98	0,92	57,32	-22,42	0,93	52,08	-22,56	0,97
0,6	35,32	-14,91	0,88	37,92	-15,71	0,91	59,33	-24,96	0,93
0,7	39,08	-19,52	0,95	40,86	-19,16	0,91	41,17	-16,96	0,97
0,8	33,38	-14,47	0,92	40,87	-17,08	0,96	43,16	-18,48	0,89
0,9	35,27	-15,65	0,98	38,35	-15,23	0,93	35,58	-15,00	0,94

Empirical parameters a and b of the equation $\ln K = a\theta + b$ e r^2 = determination coefficient.

Table 1. Empirical parameters to calculate unsaturated soil conductivity as a function of adjusted managements from data obtained in the field [1]; *taken from [10]*.

Depth (m)	Management	
	Bare	Cultivated
0,2	$3,25.10^{-3}$	$3,55.10^{-4}$
0,4	$2,07.10^{-3}$	$6,16.10^{-4}$
0,6	$4,45.10^{-3}$	$1,03.10^{-3}$
0,8	$2,79.10^{-3}$	$1,93.10^{-3}$
1,0	$3,74.10^{-3}$	$2,55.10^{-3}$
Average	$3,26.10^{-3}$ a	$1,30.10^{-3}$ b

Averages followed by the same letters differ from each other to 5% in probability by the Tukey test.

Table 2. Average hydrical conductivity of saturated soil (mh^{-1}) as a function of management systems and depth taken from Angelotti Neto & Fernandes (2005).

The soil, water reservoir for the plants, is affected by the management and culture practices, changing the dynamics and the retention of water in its pores. This retention of water in the soil matrix is controlled by two types of force, capillary and adsorption, which are denominated matric forces and originated the term matric potential of water in soil. The retention curve connects the amount of solution in the soil in equilibrium with the tension applied. It is also known that once the retention curve is obtained one can calculate, from it, the distribution of pores size in the soil. With the water retention curve or, simply, retention curve, the grower, during the management of water, will know exactly when and how much water he will need to add to the system of production to supply the plant properly with no loss of the root system for internal drainage. It was [12], in his work searching for an equation to quantify the movement of water in the soil under unsaturated conditions, who introduced in the soil science this relation between the content of water and the matric potencial. The methodology of retention curve determination had its beginning, apparently, as a [13] work that utilized a funnel fitted with a porous plate in the lower part with which potential matric values or the water retention in the soil were fixated and it measured the corresponding content of water after the equilibrium. For this reason, this kinf of funnel available in the market is also called Haines funnel [5] and it is used to determine of the most humid part of the retention curve (tension levels below 10 kPa). After that [14, 15, 16] developed a porous plate pressure chamber to measure higher tensions (10 to 2000 kPa) also known as Richards pressure chamber. Nowadays, both these devices are routine equipment to determine the retention curve in soil physics laboratories. Some variations of the funnel may be found (but the theoretical principle is the same) under names such as tension table, sand tank, etc. [17]. It is important to make it clear that the retention curve can be obtained through wetting or drying, resulting in the hysteresis phenomenon [18, 19]. In this context, to utilize the results practice, there is a need to specify the curve branch which is being used [20]. The complete retention curve of a soil (from 0 to 1500 kPa), besides reflecting the water behavior in the soil in terms of water availability for the plants, is also a reflex of the important physical properties of the soil such as texture, structure, pores distribution, consistence, etc. [21, 22, 23]. In this context, it is important to mention the recent work of [24] about the physical quality of a soil through the retention curve. Basically, what the author does is define a parameter S that is nothing but a slope of the retention curve (expressed as the content of water in the soil as a function of the tension logarithm of the water in the soil) in its inflection point and based on several arguments, the higher the S, in absolute values, the better the physical quality of the soil. As an illustration, in figure 1 below, the exemple introduced by Dexter himself [24] of two retention curves of the same degraded (or compressed) and non-degraded soil. Besides that, as regarded to water conduction through soils, the retention curve may be an alternative to the direct hydric conductivity of the soil K as a function of the content of water in the soil θ, that is, this function K (θ) can be theoretically calculated from water retention data more easily measured in laboratories. [25, 26, 27, 28, 29, 30].

In figure 2 retention curves of five different depths of Oxisol under cerrado are presented, tillage and plowing discs preparation. Data, obtained by [31], show, according to the authors, that, in the tension belt between 100 and 1500 kPa, particularly in the systems that involve cultivation, in many depths, the curves showed an aspect nearly rectilineal, asymptotic to the
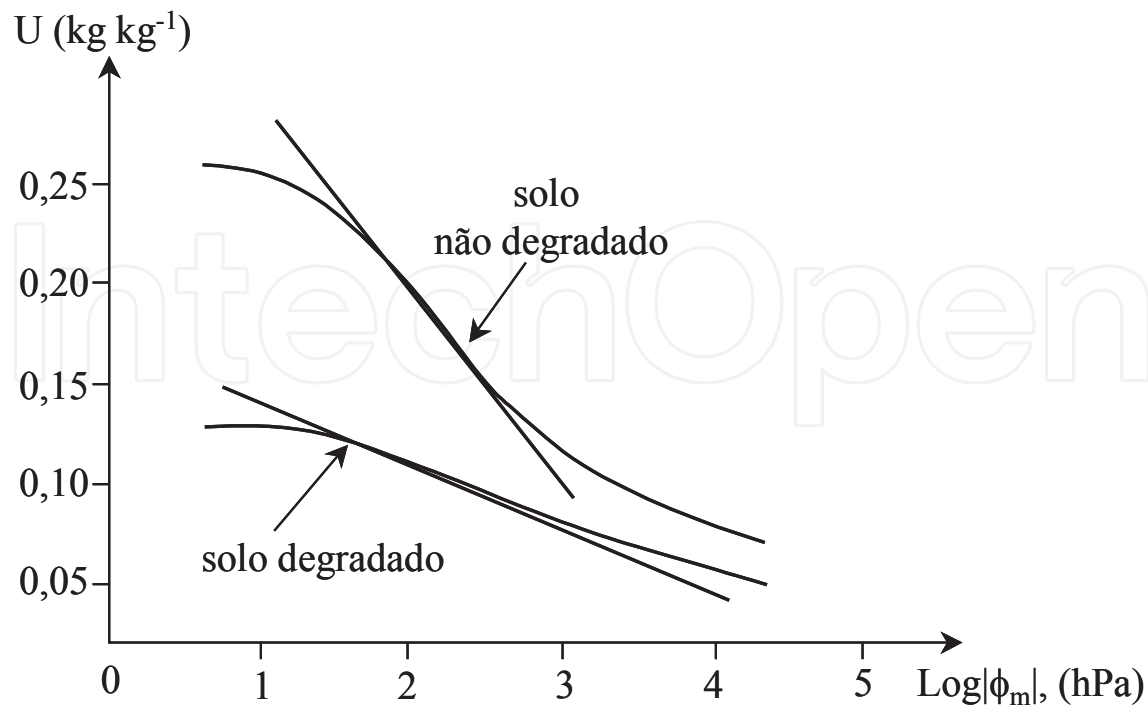
Figure 1. Retention curves of the same soil in two situations: degraded and non-degraded [24].

abscissa axis, indicating the existence of ultra-micropores with low water-storage capacity. [32] concluded, from results obtained in figure 3, that in the layer from 0,4-0,8 m, significant increase in the water retention in the soil under the irrigated system was noticed between the matric potencial of −33 to −1.500 kPa, comparing to the woods soil, due to a more expressive reduction of macropores in this soil.

Knowing how the plants utilize the water retained in the soil and how they respond to the level or storage in the profile, may be a viable solution to establish effective management strategies aiming a better possible use of water reserves in the soil by the crops. Water storage in the soil represents the water that the soil is storing in a specific layer in a specific depth. In figure 4 the results obtained by [33] are illustrated and determine the variation of water storage in the soil for three managements, between current humidity and PWP, for eight different redistribution times and five depths in determination experiment of function K(θ) by the instantaneous profile method. They concluded that until the 0,25 m layer, the under rainfed soil always retained more water than the woods soil and irrigated, having a higher variation between the woods and two other management systems.

Nitrogen leaching is extremily important because it can decrease the quantity of ammonium and nitrate in the topsoil sensibly and, consequently, reduce the nutrient availability; when in excess, leaching constitutes a potential danger of groundwater contamination by nitrate [34]. Over the last few decades, surface and underwater sources contamination with nutrients, particularly N and P, has become a significant subject for people in general,
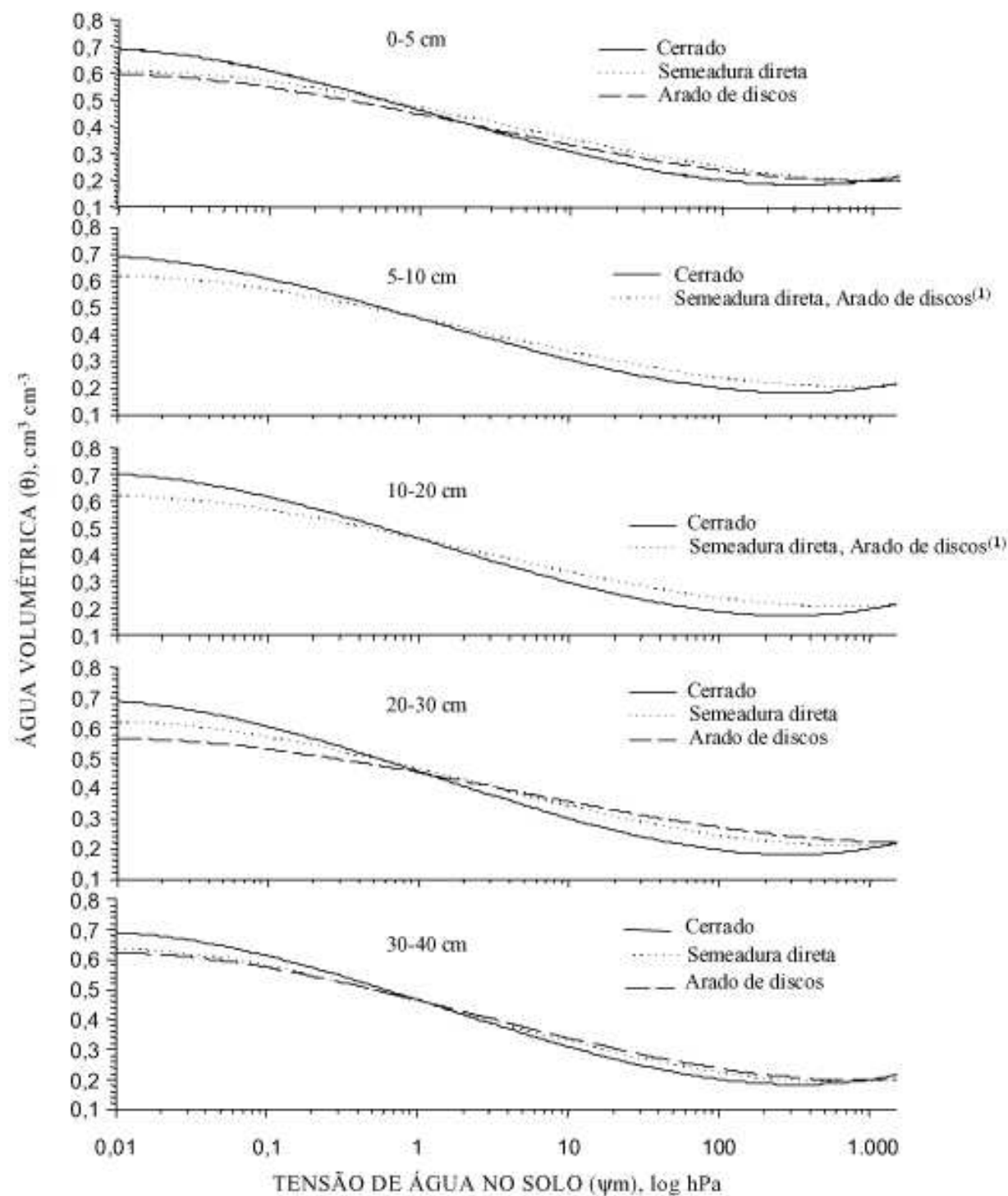
Figure 2. Retention curves of five different depths of Oxisol under cerrado, tillage and plowing discs preparation [31].

including the farmers. High concentrations of nitrate in the water for human consumption are worrying, as they cause methemoglobinemia, commonly known as blue baby syndrome. This is a problem that occurs only in children under six months old and pregnant women. Besides that, water contamination by nitrates and P has been connected with

another abnormality denominated hypoxia (low oxygen levels) in water from Gulf of Mexico, which inhibits the production of shrimp and other acquatic species in this region [35]. For the USA, the maximum concentration of nitrate for water to be considered potable and not cause any harm to human health is 10 mg L^{-1} and 1mg L^{-1}, respectively, being the same values adopted by Brazilian Legislation, but for the European Union the accepted value of nitrate reaches 50 mg L^{-1} [36]. N leaching occurs in descending order for NO_3^- > NH_4^+ > Organic-N. Most leaching in form of nitrate occurs due to its negative charge being repelled by soil colloids where the same charge prevails [37]. The amount of N that is lost in leaching varies a lot according to the N dose, the method of application of fertilizers, the speed of mineralization and immobilization by plants and microorganisms, the amount of rain and the soil properties that influence its capacity to retain water, whichever are the texture, structure and porosity [38]. To quantify the elements due to leaching, it is necessary to know the water flow density in the soil and the element concentration in the soil solution, since their product generates the flow density of the element in the soil. The water flow density in the soil represents the water flow per unit cross-sectional area of soil and may be determined by Darcy-Buckingham equation [5]. Studies about water dynamics in field conditions emphasizing water flow in the crop root zone are not frequent and, often, incomplete, due to the great complexity of the necessary experimental procedures. However, as mentioned previously, knowing internal drainage is essential to estimate the leaching of chemicals down to the root system of the crop under analysis. When [39] assessed a nitrate leaching (total and provenient from fertilizers) to 0,80 m depth, in a succession of cultures corn-black oat-corn, under no-tillage implementation, utilizing fertilizer labeled ^{15}N, they obtained the results that are presented in Chart 3. It can be observed through the data in the chart, as concluded by the authors, that total leaching nitrate loss to 0,80 m depth, in the first corn crop, in 120 kg ha^{-1} of N dose, was approximately 96 and 68 kg ha^{-1}, for parcelling with 60 kg ha^{-1} and 30 kg ha^{-1} of N in sowing, respectively, of which only 3 and 1 kg ha^{-1} of N were provenient from the nitrogen-rich fertilizer. In the second year of cultivation, nitrate leaching was far lower than compared to the first year and the leachate nitrate provenient from the fertilizer was negligible (average 0,23%).

[40] continuing studies with leaching in the crop succession consisted of: maize in 2006 followed by brachiaria plus fallow and finally maize in 2007. Internal drainage decreased with the increase of applied N levels to the crop succession, changing from 31.5 to 73.4 % of the total rainfall (97 mm) in the first maize, from 26.1 to 58.1 % of the total rainfall (695 mm) in brachiaria + fallow, and from 56.6 to 87.4 % of the 419 mm of total rainfall in the second maize crop. The leaching of total nitrate (from fertilizer and other sources) was very low in the first maize crop for all applied N levels and significant for the rates of 120 and 180 kg ha-1 in the periods of brachiaria plus fallow (26.16 for 120 kg ha-1 and 39.8 for 180 kg ha-1) and of the second maize crop (approximately 23 kg ha-1 for both levels). There was no N leaching from fertilizer in the first maize crop and N leaching was very low in the brachiaria and second maize crop.
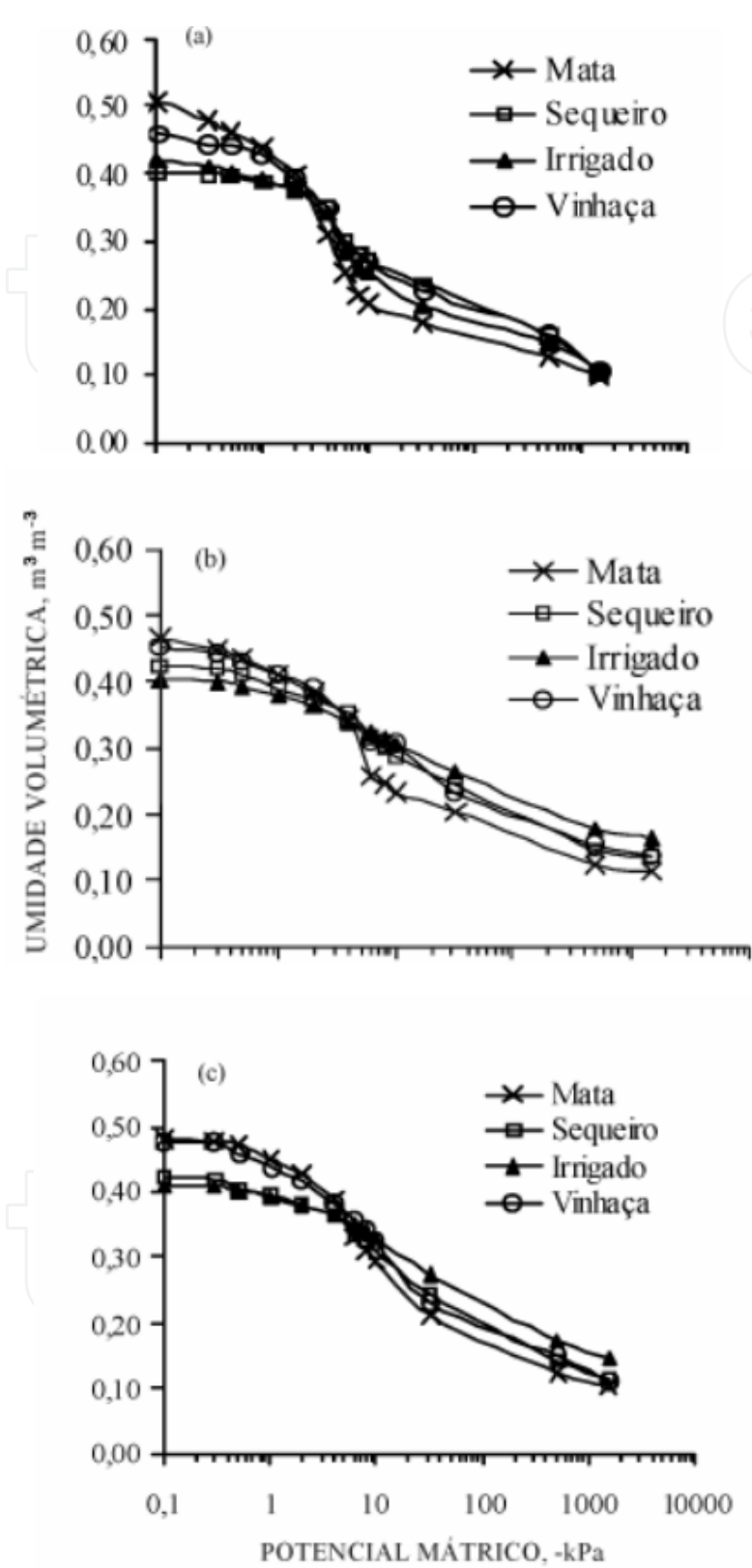
Figure 3. Retention curves in the layers (a) 0-0,2 m, (b) 0,2-0,4 m e (c) 0,4-0,6 m, for the use and management of the soils studied systems [32].
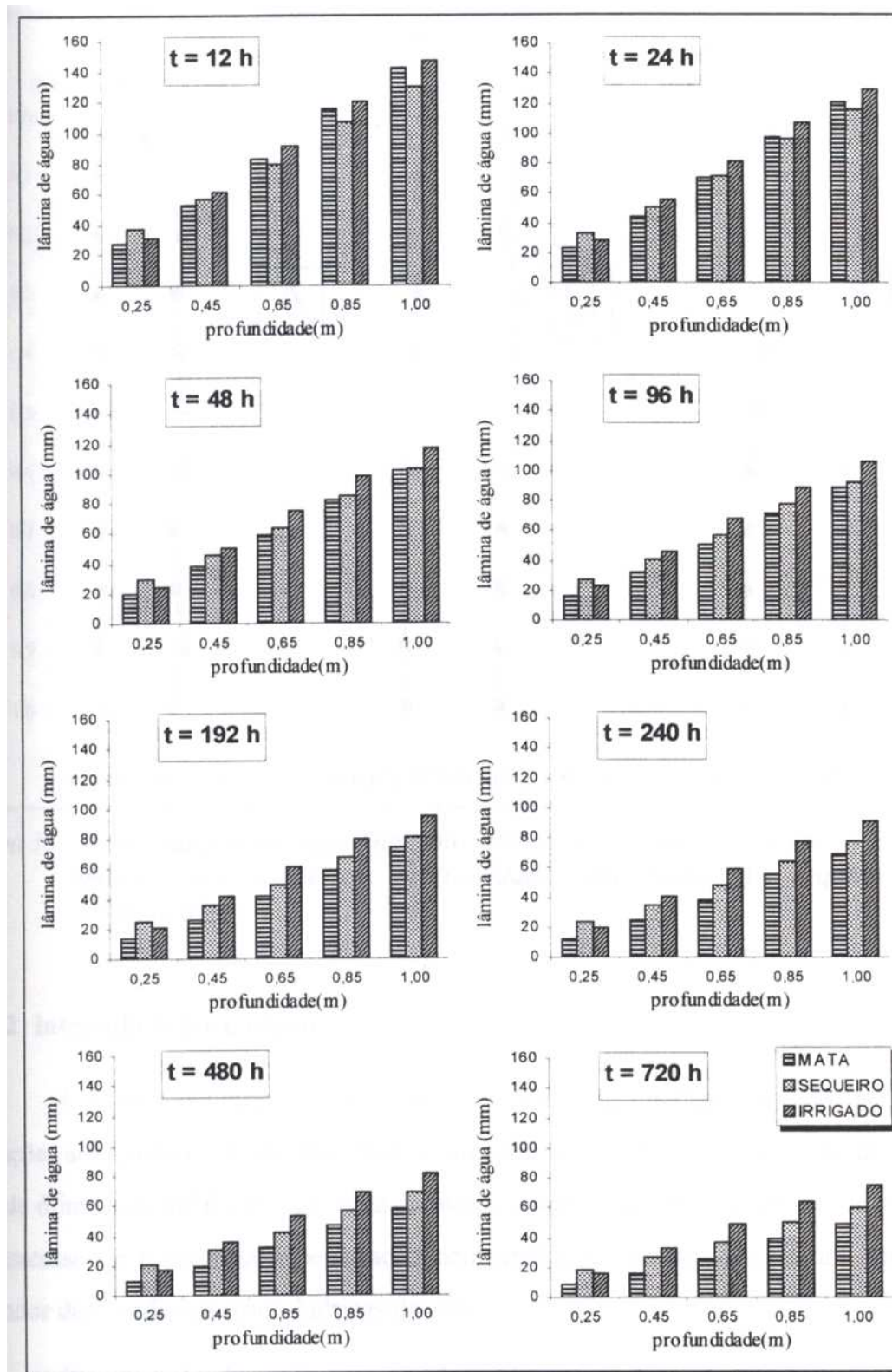
Figure 4. Variation of water storage in the soil for three managements, between the current humidity and PWP, for eight different drainage times and five depths [33]

Treatments		DAE	Corn cultivation – harvest 2003/2004			
1	2		Precipitation (mm)	Water drainage to 0,80 m (mm)	Leaching-NO$_3^-$ (kg ha^{-1})	
					Total	PF
30	90	0-30	110,1	103,62 a	10,27 a	0,20 a
60	60			129,91 a	13,97 a	0,18 a
30	90	30-60	200,6	165,67 a	33,14 a	1,79 a
60	60			180,11 a	20,00 b	0,28 b
30	90	60-90	239,4	155,71 b	24,93 b	0,94 a
60	60			218,63 a	61,64 a	0,86 a
30	90	90-120	64,9	1,54 b	0,01 a	0,07 a
60	60			3,65 a	0,01 a	0,07 a
30	90	Total	615,0	**426,54 b**	**68,35 b**	**3,00 a**
60	60			**532,29 a**	**95,61 a**	**1,39 b**

Treatments			Between the first corn cultivation and black oat			
1	2		Precipitation (mm)	Water drainage to 0,80 m (mm)	Leaching -NO$_3^-$ (kg ha^{-1})	
					total	PF
30	90	Total	296,0	151,18 b	2,81 b	-
60	60			243,24 a	4,77 a	-

Treatments		DAE	Black oat – harvest 2004			
1	2		Precipitation (mm)	Water drainage to 0,80 m (mm)	Leaching -NO$_3^-$ (kg ha^{-1})	
					total	PF
30	90	0-40	0,0	6,68 b	0,00 a	-
60	60			11,88 a	0,00a	-
30	90	40-80	146,5	15,02 b	0,62 b	0,01 a
60	60			61,69 a	2,64 a	0,02 a
30	90	Total	146,5	**21,70 b**	**0,62 b**	**0,01 a**
60	60			**73,57 a**	**2,64 a**	**0,02 a**

Treatments			Between black oat and the second corn cultivation			
1	2		Precipitation (mm)	Water drainage to 0,80 m (mm)	Leaching -NO$_3^-$ (kg ha^{-1})	
					total	PF
30	90	Total	136,3	56,78 b	0,07 a	-
60	60			142,14 a	0,03 a	-

Treatments		DAE	Corn cultivation - harvest 2004/2005			
1	2		Precipitation (mm)	Water drainage to 0,80 m (mm)	Leaching -NO$_3^-$ (kg ha^{-1})	
					total	PF
30	90	0-30	181,9	113,16 b	4,80 a	-

60	60			180,17 a	6,45 a	-
30	90	30-60	231,7	132,50 b	11,79 a	-
60	60			211,40 a	9,80 a	-
30	90	60-90	78,4	0,61 b	0,00 a	-
60	60			4,74 a	0,00 a	-
30	90	90-120	164,4	133,37 a	6,43 b	0,13 a
60	60			134,59 a	12,12 a	0,13 a
30	90	**Total**	**656,4**	**379,64 b**	**23,02 a**	**0,13 a**
60	60			**530,90 a**	**28,37 a**	**0,13 a**

Obs. The treatments 30-90 and/or 60-60 refer to the application of N in the sowing in the 6-8 leaf stage. DAE stands for "days after emergency". Averages followed by the same letter do not differ from each other in significance level 5% by Tukey test. 1 and 2 refer to the nitrogen fertilization in corn, respectively in the sowing and coverage.

Table 3. Water drainage and total nitrate leaching provenient from the fertilizer (PF) to 0,80 m depth, in the succession corn-black oat-corn [39]

3. Conclusions

Conservative management systems, such as tillage, present an expressive improvement effect in the hydro-physical quality of tropical and subtropical soils. The soil in function of type has diverse physical, chemical and biological composition, making it difficult to have a pattern for the amount of hydro-physical indicators to evaluate their quantity. Therefore, there is a need for more detailed studies, particularly for tropical conditions that can define more precise values for the indicators of quality. Different types of soil have a great influence in the leaching process magnitude, however, other factors such as organic matter content, dose, type and time of fertilizer application, mainly the nitrogen-rich one, and also the weather, have great influence in this process. Thus, leaching studies aiming the use of fertilizers and their interaction with different soil managements are influential to Brazilian research, since there is a great lack of results for soils in tropical and subtropical weather countries.

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References

[1] Doran, J.W.; Parkin, T.B. *Defining and assessing soil quality*. In: DORAN, J. W. et al. (Eds.). Defining soil quality for a sustainable environment. Madisson: ASA/SSSA, 1994. p-3-21.

[2] Watson, K.K. An instantaneous profile method for determining the hydraulic conductivity of unsaturated porous materials. *Water Resources Research*, 1996; 2 709-715.

[3] Hillel, D.A; Krentos, V.K.; Stilianov, Y. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in situ. *Soil Science.*, 1972; 114, 395-400.

[4] Libardi, P.L.; Reichardt K.; Nielsen, D.P.; Biggar, J.W. Simple field methods for estimating soil hydraulic conductivity. *Soil Science Society of American journal*, 1980; 44, p. 3-7.

[5] Libardi, P.L. *Dinâmica da água no solo.* 2.ed. São Paulo: Editora da Universidade de São Paulo, 2005. 329p.

[6] Greacen, E.L. Soil water assessment by neutron method. CSIRO. Austrália, 140p, 1981.

[7] Carvalho, L.A. de. Condutividade *hidráulica do solo no campo: as simplificações do método do perfil instantâneo*, 2003. Tese (Mestrado) – "Escola Superior de Agricultura Luiz de Queiroz", Universidade de São Paulo, Piracicaba, 2003.

[8] Topp, G.C.; Davis, J.L.; Annan, A.P. Eletrotromagnetic determination of soil water content: measurement in coaxial transmission lines. *Water Resources Research*, 1980; 16(3): 574-582.

[9] Smith, K.A.; Mullins, C.E. Soil analysis-physical methods. New York: s.ed., 1991. 620p.

[10] Klein, V.A.; Libardi, P.L. Condutividade hidráulica de um Latossolo Roxo não saturado, sob diferentes sistemas e manejo. *Ciência Rural*: Santa Maria, 2002; 32 (6), 945-953.

[11] Angelotti Neto, A.; Fernandes, E.J. Condutividade hidráulica de um Latossolo Vermelho em pousio e cultivo intensivo. *Pesquisa Agropecuária Brasileira*, 2005; 40 (8), 797-802.

[12] Buckhingham, E. *Studies of the movement of soil moisture*. USDA Bur. Soil Bull. 38. US Government Printing Office. Washington D.C., 1907.

[13] Haines, W.B. Studies in the physical properties of soil: V. The hysteresis effect in capillary properties and the models of misture associated therewith. *Jounal Agronomy. Science*, 1930; 20, 97-116.

[14] Richards, L.A. A pressure membrane extraction apparatus for soil solution. *Soil Science*, 1941; 51, 377-386.

[15] Richards, L.A. Pressure membrane apparatus – construction and use. *Agronomy. Engineer*, 1947; 28, 451-454.

[16] Richards, L.A. Methods of measuring soil moisture tension. *Soil Science*. 1949; 68, 95 – 112.

[17] Kutílek, M; Nielsen, D.R. *Soil Hydrology*, Catena Verlag, Germany, 1994, 370p.

[18] Poulovassilis, A. The influence of the initial water content on the redistribution of soil water after infiltration. *Soil Science*, Baltimore, 1983; 135, p. 265-281.

[19] Klute, A. Water retention: laboratory methods. In BLACK, C.A., ed. Methods of Soil Analysis. I Physical and mineralogical methods. Madison, Winconsin, American Society of Agronomy, Inc., *Soil Science Society of America*, Inc. Publisher, 1986, 635-662.

[20] Moraes, S.O. *Heterogeneidade hidráulica de uma terra roxa estruturada*. Piracicaba, 1991, 141p. (Doutorado – Escola Superior de Agricultura "Luiz de Queiroz"/USP), 1991.

[21] Sharma, M.L; Uehara, G. Influence of soil structure on water relations in low humic latosols: J. Water retention. *Soil Science Society America Journal*, Madison, 1968; 32, 765-770.

[22] Reeve, M.J.; Smith, P.D.; Thomasson, A.J. The effect of density on water retention properties of field soils. *Journal of Soil Science*, Oxford, 173; 24, 355-367.

[23] Rawls. W.J. e Pachepsky, Y.A. Soil Consistence and Structure as predictors of water retention. *Soil Science Society. American. Journal*, 2002, 66, 1115-1126.

[24] Dexter, A.R. Soil physical quality – Part I. Theory, effects of soil texture, density and organic matter and effects on root growth. *Georderma*, 2004; 120, 201-214.

[25] Childs, E.C.; Colins George, N. The permeability of porous materials. Proc. Roy. Soc., *London, Ser. A*. 1950; 201, 392-405.

[26] Burdine, N.T. Relative permeability calculations from pore-size distribution data. *Petroleum Trans. Am. Inst. Mining Eng.*, 1953; 198, 71-77.

[27] Marshall, T.J. A relation between permeability and size distribution of pores. *Journal Soil Science*, v. 9, p. 1-9, 1958.

[28] Millington, R.J.; Quirk, J.P. Permeabilty of porous solids. Trans. *Faraday Society*., 1961; 57, 1200-1207.

[29] Mualem, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 1976; 12, 513-522.

[30] Van Genuchten, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society America Journal*, 1980; 44, 892-898.

[31] Oliveira, G.C.; Dias Júnior, M.C.; Resck, D.V.C.; Curi, N. Caracterização química e físico-hídrica de um Latossolo Vermelho após vinte anos de manejo e cultivo do solo. *Revista Brasileira de Ciência do Solo*, 2004; 28, 327-336.

[32] Silva, A.J.N.; Cabeda, M.S.V.; Lima, J.F.W.F. Efeito de sistemas de uso e manejo nas propriedades físico-hídricas de um argissolo amarelo de tabuleiro costeiro. *Revista Brasileira de Ciência do Solo*, 2005; 29,.833-842.

[33] Klein, V.A.; Libardi, P.L. *Propriedades físico-hídrico-mecânicas de um Latossolo Roxo, sob diferentes sistemas de uso e manejo*. 150 p., 1998. Tese (Doutorado em Solos e Nutrição de Plantas) – Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, Piracicaba, 1998.

[34] Stark, J.C.; Jarrel, W.M.; Letey, J. Evaluation of irrigation-nitrogen management practices for celery using continous-variable irrigation. *Soil Science Society American Journal*, Madison, 1980; 47, 95-98.

[35] Hoeft, R.G. *Desafios para a obtenção de altas produtividades de milho e de soja nos EUA*. Piracicaba: Potafos, p.1-4, 2003 (Informações Agronômicas, 104).

[36] Tundisi, J.G. *Água no Século XXI*: Enfrentando a escassez. São Carlos: RiMa IIE, 2003. 248p.

[37] Gonçalves, C.N.; Ceretta, C.A.; Basso, C.J. Sucessões de culturas com plantas de cobertura e milho em plantio direto e sua influência sobre o nitrogênio do solo. *Revista Brasileira de Ciência do Solo*: Viçosa, 2000; 24, 153-159.

[38] Kiehl, J.C. Nitrogênio: Dinâmica e disponibilidade no solo. In: ___. *Curso de atualização em fertilidade do solo*. Campinas: Fundação Cargill, 1987. p.139-157.

[39] Fernandes, F.C.S.; Libardi, P.L.; Carvalho, L.A. Internal Drainage and nitrate leaching in a corn-black oat-corn sucession with two split nitrogen applications. Scientia Agricola, Piracicaba, 2006; 63, 483-492.

[40] Fernandes, F.C.S.; Libardi, P.L. Drenagem interna e lixiviação de nitrato em um Latossolo sob sucessão milho-braquiária-milho, com diferentes doses de nitrogênio. *Revista Brasileira de Ciência do Solo*, Viçosa, 2009, 33, 1163-1173.