Least limiting water range and S index to evaluate some soil physical quality in the northeast Brazil

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Abstract
The concern with soil physical quality has grown in recent years, particularly due to serious problems caused by soil use. The objective of this research was to evaluate the soil physical quality of irrigated areas in the State of Ceará, Brazil, through the use of the Least limiting Water Range (LLWR) and the S index. Undisturbed soil samples were collected at 5-10cm depth in three areas, natural vegetation (NV), area under banana cultivation (B) and a pasture area (P), all located in Jaguaribe-Apodi Irrigated District, Limoeiro do Norte, Ceará, Brazil. The LLWR was determined using the water retention curve, the soil resistance to penetration and soil bulk density, parameters needed to obtain the upper and lower limit. The S index was obtained from the water retention curve. The S index was sensitive to soil structure alterations caused probably by tillage. The variation of the LLWR differed between the studied areas as a function of the soil bulk density. The LLWR and S index seem to be good indicators of soil physical quality, and it was noticed that soils under cultivation suffer an alteration of their structure compared to soils under natural vegetation.

Key Words
Soil water retention curve, soil resistance to penetration, inflection point, soil degradation, soil structure

Introduction
Soil physical quality is a concept of growing interest in recent years due to the knowledge that soil use may cause disturbance, and consequently, reduce its capacity for sustainable production (Silva *et al.,* 2007). The Least Limiting Water Range (LLWR) is an indicator of soil physical quality and soil structure that joins in only one parameter the effects of bulk density, aeration, soil resistance to penetration and soil water retention on the development of plants, being capable to indicate situations of stress (Tormena *et al.,* 1998; Leão, 2002). The S index was first proposed by Dexter (2004) as an indicator of soil physical and structural quality, based on the water retention curve (WRC), where the inflection point curvature is zero, corresponding to the S index. Being in a semi-arid region, the area of Jaguaribe-Apodi in the State of Ceará, Brazil, is dependent on irrigation practices to be productive, with soil degradation resulting from intensive use and inadequate soil practices. Thus, this study was conducted to evaluate the soil physical quality of irrigated cultivated areas compared to areas under natural vegetation, in the State of Ceará, Brazil, through the use of the LLWR and S index.

Methods
Site location and description of soils
The areas for the study are located in the Jaguaribe-Apodi Irrigated District, Limoeiro do Norte, Ceará State, Brazil, and classified as Haplic Cambisols (Embrapa, 2006). The climate of the region is BSw'h', characterized as hot and semi-arid. It has an annual maximum and minimum temperature of 36ºC and 22ºC, respectively, with annual mean temperature of 28.5°C. The area receives approximately 772 mm of annual mean precipitation, with an annual mean potential evapotranspiration of 3215 mm and annual relative humidity of 62%. The dominant relief of the region is regular, uniform, very soft declivity, varying between 0.5 – 1.5%, and situated 100 m above sea level (DNOCS, 2009). The selected areas were as follows: Banana (B) (5°9'15" S and 37°59'55" W), cultivated with banana cv. "Prata anã" irrigated daily during the dry season (June-December) with microsprinklers; the machines used in the area is tractor with subsoiling. Second, a Pasture area (P) (5°12'54" S and 38°01'52" W), cultivated for 10 years with "capim tifton" (*Cynodon niemfluesis*) and irrigated with center pivot irrigation systems. Also during the dry season, the machines used in the area during the haymaking are: line trimmer, hay bob, baling press and tractors, and, third, an area without agricultural management under natural vegetation (NV) located next the cultivated areas, considered

as a reference area.

Sampling and analysis
Undisturbed soil samples (5-cm diam. by 5-cm length on average) were collected at 5-10cm depth, saturated with water and split into twelve groups, each of which were equilibrated on pressure plates at twelve matric pressures: -10; -20; -40; -60; -80; -100; -300; -500; -800; -1000; -5000 and -15000 KPa (Klute, 1986). After equilibration, samples were weighed and soil resistance to penetration (PR) was measured on each sample with an electronic penetrometer, with a constant speed penetration of 1 cm min^{-1}. The samples were then oven dried at 105 ºC for 48h and the water content and bulk density determined (Blake and Hartge, 1986). The values of PR data were regressed against θ and *D*s using the model proposed by Busscher (1990), described as follows: PR = $a\ \theta^b\ Ds^c$ [1], where PR is the penetration resistance (MPa), Ds is the bulk density (Mg m^{-3}), θ is the volumetric humidity ($m^3\ m^{-3}$) and, *a, b* and *c* are constants.

The least limiting water range was determined following the methodology described by Silva *et al.* (1994) and Tormena *et al.* (1998). The critical values of humidity associated with the matric potential, penetration resistance and air-filled porosity were selected from the literature: field capacity (θ_{FC}) at -0.01 MPa (Reichardt, 1988); permanent wilting point (θ_{PWP}) at -1.5 MPa (Savage 1996); penetration resistance (θ_{PR}) at 2.0 MPa (Taylor, 1966) and air-filled porosity (θ_{PA}) at 0.10 $m^3\ m^{-3}$ (Grable and Siemer, 1968). At each Ds the LLWR is the difference between the upper limit and the lower limit. The upper limit is the drier θ of either θ_{FC} or θ_{PWP} whereas the lower limit is the wetter θ of either θ_{PWP} or θ_{PR} (Silva *et al.* 1994).

To the elaboration of the soil water retention curve (SWRC) were used three samples of each area for each pressure and adjusted according to the equation [2] proposed by van Genuchten (1980):

$$\theta = \theta r + \frac{(\theta s - \theta r)}{\left[1 + (\alpha\psi)^n\right]^m} \qquad [2]$$

where, θ is the water content ($m^3\ m^{-3}$); θs is the saturated water content ($m^3\ m^{-3}$); θr is the residual water content ($m^3\ m^{-3}$); ψ is the matric potential (MPa); *α* and *n* are constants; *m* was considered independent of *n*, being equivalent to 1-1/n. The van Genuchten model (1980) was used to calculate the inflection point values of the water retention curve; this is the S index value, using the equation [3]:

$$S = -n.(\theta s - \theta r).\left[1 + \frac{1}{m}\right]^{-(1+m)} \qquad [3]$$

The negative sign associated to the *n* parameter of equation [3] was corrected once the adjustment of the SWRC was done considering the matric potential, consequently, facilitating the discussion of the results. An S value of 0.035 was established as the limit between soils with good and poor soil structural quality (Dexter, 2004).

All samples were analyzed using orthogonal contrasts from the unfolding of the two degrees of freedom for each treatment. The contrasts were tested by the *F* test (P< 0.01) against the mean square of the residue gotten by the analysis of variance, in a completely randomized design with three replications. The natural vegetation area (NV) was compared against the Banana area resulting in the contrast C1. The contrast C2 compared the NV against the Pasture area, and, the contrast C3 compared the two cultivated areas.

Results
The estimated soil physical quality data using the S index are shown in Table 1, where van Genuchten parameters of the model were highly influenced by the soil management practices as observed by the coefficients. The θsat parameter was significant (P<0.05) for the contrast C1 and C2, being higher for the NV area, followed by Banana and Pasture areas. The θr and *m* parameters were significant (P<0.01) for contrast C2, *n* was significant (P<0.05) for contrast C1 and C2, and S was also significant for contrast C1 and C2 (P<0.01) and for contrast C3 (P<0.1). The S index varied in function of the soil management systems, revealing to be a good sensitive parameter to describe the soil structure alterations. The pasture area showed an index of 0.028, lower to the limit between a good and poor soil structural quality, probably having an inadequate pore distribution, consequently having unfavorable physical conditions for root development.

The four limiting water contents, i.e., θ_{FC}, θ_{PWP}, θ_{PR}, and θ_{PA}, as well as the LLWR for each observed *Ds* are shown in Figure 1. Shaded areas represent the LLWR, where the upper limit corresponds to θ_{PA} from Ds values of 1.54, 1.59 and 1.57 Mg m^{-3}, for natural vegetation, banana and pasture areas, respectively. These high values of bulk density can be associated to an inadequate root development influenced by poor oxygen diffusion. The θ_{PR} defined the lower limit, but, the higher influence of the LLWR was also found in various soils with different soil textures, from clayed soils (Tormena *et al.,* 1998) to silt and sandy loam (Silva *et al.,* 1994).

The area under natural vegetation did not show LLWR null values for the Ds (Figure 1A), that combined with the high value of the S index, confirming the indications that soils under natural vegetation generally have better physical properties (Reynolds *et al.,* 2002). On the other hand, in the areas under cultivation, were observed either increases on the θ_{PR} and declines on the θ_{PA} as a consequence of the rise in the Ds, in agreement with the results showed by Silva *et al.* (1994). The LLWR narrowing observed in Figures 1B and 1C characterized the losses of physical soil quality as a result of the stress caused by the soil management under the cultivation areas, as stated by Silva and Kay (1996). Crops grown on soils that have a narrow LLWR are hypothesized (Kay, 1989) to be more vulnerable to both drought and excess wetness than soils having a wider LLWR.

The total variation extent of the LLWR was less for the area under pasture cultivation in comparison to the other two areas, varying from 0.27 to 0.31 m^3m^{-3} for θv and from 1.51 to 1.61 Mg m^{-3} for bulk density. This lower extent of the LLWR in conjunction with the lower S index value, characterize the loss of soil physical quality, where the soil humidity at the moment of soil tillage during the haymaking could contribute to the significant increase of soil degradation in the area.

Table 1. Water retention curve coefficients for the van Genuchten model (θsat, θres, α, m, n), coefficient of determination (R^2) and S index of the cultivated areas and under natural vegetation in the Jaguaribe-Apodi Irrigated District, Ceará State, Brazil.

	van Genuchten Parameters						
Area/	***θsat***	***θres***	***A***	***m***	***n***	***S***	**R^2**
Contrast	**m^3 m^{-3}**						
NV	0.465	0.179	0.106	0.163	10.95	0.062	1
B	0.387	0.199	0.217	0.266	1.915	0.041	1
P	0.375	0.169	0.219	0.167	1.598	0.028	1
	Orthogonal contrast						
C1	**	ns	ns	ns	**	***	
C2	**	*	ns	*	**	***	
C3	ns	ns	ns	ns	ns	*	

NV: Natural Vegetation; **B:** area under Banana cultivation; **P:** area under Pasture cultivation. ***θsat***: saturated water content; ***θres***: residual water content; ***α***, ***m*** e ***n***: van Genuchten parameters; **C1** = (B *vs* NV); **C2** = (P *vs* VN); **C3** = (B *vs* P). ***, **, * and ns = significant at 1%, 5%, 10% and not significant, respectively.

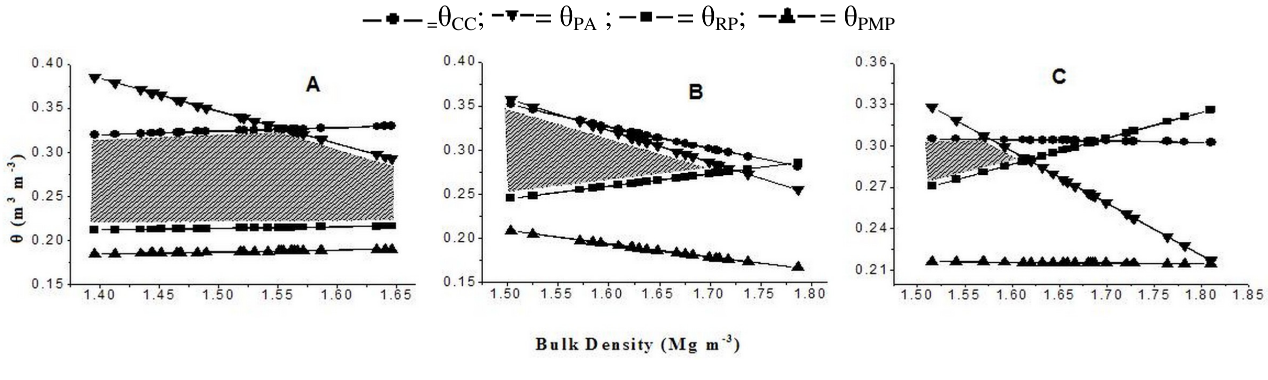

Figure 1. Variation of water content in function of the bulk density (Mg m^{-3}) under the critical levels of field capacity (ψ = -0.01 MPa), permanent wilting point (ψ = -1.5 MPa), air-filled porosity of 10% and penetration resistance of 2 MPa, at a 5-10 cm depth in areas under Natural Vegetation (A), under Banana cultivation (B) and under Pasture cultivation (C). Shaded areas represent the LLWR.

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Conclusion
Both, the LLWR and S index showed to be good indicators of soil physical quality in irrigated areas in the State of Ceará, Brazil, where soils under intensive cultivation might lead to detrimental effects in some properties as structural degradation compared to areas under natural vegetation. It is time for these areas to turn into no-till management especially if they are predicted to be a long-term soil use.

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