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REVISÃO DE LITERATURA

BEYOND THE “LEAST LIMITING WATER RANGE”: RETHINKING SOIL PHYSICS RESEARCH IN BRAZIL(1)

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ABSTRACT

As opposed to objective definitions in soil physics, the subjective term “soil physical quality” is increasingly found in publications in the soil physics area. A supposed indicator of soil physical quality that has been the focus of attention, especially in the Brazilian literature, is the Least Limiting Water Range (R_{LL}), translated in Portuguese as "Intervalo Hídrico Ótimo" or IHO. In this paper the four limiting water contents that define R_{LL} are discussed in the light of objectively determinable soil physical properties, pointing to inconsistencies in the R_{LL} definition and calculation. It also discusses the interpretation of R_{LL} as an indicator of crop productivity or soil physical quality, showing its inability to consider common phenological and pedological boundary conditions. It is shown that so-called “critical densities” found by the R_{LL} through a commonly applied calculation method are questionable. Considering the availability of robust models for agronomy, ecology, hydrology, meteorology and other related areas, the attractiveness of R_{LL} as an indicator to Brazilian soil physicists is not related to its (never proven) effectiveness, but rather to the simplicity with which it is dealt. Determining the respective limiting contents in a simplified manner, relegating the study or concern on the actual functioning of the system to a lower priority, goes against scientific construction and systemic understanding. This study suggests a realignment of the research in soil physics in Brazil with scientific precepts, towards mechanistic soil physics, to replace the currently predominant search for empirical correlations below the state of the art of soil physics.

Keywords: modeling, field capacity, drought stress, mechanical stress, anoxic stress.

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RESUMO: *ALÉM DO "INTERVALO HÍDRICO ÓTIMO": REPENSANDO A PESQUISA EM FÍSICA DO SOLO NO BRASIL*

Em oposição a definições objetivas da física do solo, o termo subjetivo "qualidade física do solo" aparece com frequência cada vez maior em trabalhos publicados da área. Um suposto indicador de qualidade física do solo que recebe muita atenção, especialmente na literatura brasileira, é o Intervalo Hídrico Ótimo (I_{HO}), definido por quatro teores-limite de água. Nesse texto, discutem-se seus quatro teores-limite à luz de propriedades físicas do solo determináveis objetivamente, apontando-se incoerências na definição e no cálculo do I_{HO}. Discute-se a interpretação do I_{HO} como indicador da produtividade das culturas ou da qualidade física do solo, demonstrando-se sua incapacidade de abranger condições de contorno fenológicas e pedológicas comuns. Demonstra-se, também, que as densidades críticas encontradas pelo I_{HO} por método comumente empregado são questionáveis. Considerando a disponibilidade de modelos comprovadamente robustos para as áreas de agronomia, ecologia, hidrologia, meteorologia e outras conexas, a popularidade do I_{HO} como indicador na física do solo brasileira não pode ser entendido pela sua eficácia, pois essa nunca foi comprovada, mas deve ser explicado pela simplicidade com que ele é tratado. A determinação dos respectivos teores-limite de forma simplificada, deixando o estudo ou a preocupação com o real funcionamento do sistema para o segundo plano, vai à contramão da construção científica e do entendimento sistêmico. Sugere-se um realinhamento da pesquisa em física do solo no Brasil com os preceitos da ciência, na direção da física do solo mecanística em detrimento da busca por correlações empíricas aquém do estado da arte em física do solo.

Palavras-chave: modelagem, capacidade de campo, estresse hídrico, estresse mecânico, estresse anóxico.

INTRODUCTION

Soil physics is the branch of soil science that deals with soil physical properties and processes. The resulting knowledge is used to predict the behavior of natural or managed ecosystems. To this effect, soil physics focuses on measuring and modeling the dynamics of physical soil components, comprised of mineral and organic solids, water, solutes and soil air, as well as heat flows in the soil system. A dissociation of measurement and modeling generates a limited and fragmented understanding of the systems of interest to soil physics and it is common practice that soil physicists develop instruments to measure the properties of interest, construing them in the light of hypotheses on the operation of the studied system. Soil physicists translate the evolution of hypotheses and the increased associated knowledge into models or algorithms, allowing a quantitative prediction of system variables in time and space.

As opposed to objective definitions of soil physics, the subjective term "soil physical quality" has appeared more and more often in studies published in the area of soil physics. Whereas "soil physics" is a clearly defined field of science, "soil physical quality" has no absolute definition. In contrast with objectively defined soil properties like conductivities and diffusivities with exact dimensions following from their physical definition, "quality" has no defined dimension. From the agricultural point of view, the inherent subjectivity of the term "soil physical quality" can be translated objectively by soil physics into properties of transfer and storage of mass and energy that correspond to contents of water, solutes, air and heat. These contents will then be appropriate to maximize the development of crops, minimize environmental degradation, and ensure soil structural stability to maintain its biological health and allow root growth.

Specific models have been developed aiming to predict and assess such processes. These models are primarily based on the physical and physicochemical description of mass and energy transfer processes in the soil and in the soil-plant-atmosphere system and allow the quantitative assessment of the adequacy of soil conditions to crop requirements. The development, calibration, validation, sensitivity analysis and the use of such models have engaged soil scientists worldwide. After defining a scenario, it is translated into input parameters for the respective model, allowing prediction of the system behavior subject to the established boundary conditions. Examples of well-known models of this type are *Hydrus* (Simunek and Van Genuchten, 2008), *SWAP* (Kroes et al., 2008) and *SWAT* (Arnold et al., 2012), among many others. The models differ in process description and the dimensions of the simulated system (1-D, 2-D or 3-D), the method of solving numerical problems (implicitly or explicitly) or the emphasis given to one or another sub-process. Under this systemic approach, soil physicists have advanced in objectively understanding how the system works, something that is intangible under the subjective approach of "soil physical quality".

In an attempt to avoid dealing with the complex relations that govern the system and the assessment of the input parameters required by the respective models, indicators of the system status have been suggested to address more specific or simpler manifestations of a system. An indicator cannot only provide information on the progress of a system towards a given goal, but can also be understood as a tool that helps perceive a tendency or a phenomenon that, otherwise, would not be easily detected (Hammond et al., 1995). Indicators sometimes just represent a characteristic of the system or are calculated as a function of some characteristics by an empirical formula. By name, "indicator" means something that indicates, suggests, and one cannot expect that an indicator will determine or provide predictions of system behavior. Thus, several indicators can be used to understand something as complex as "soil physical quality". Soil aggregate stability (Jastrow et al., 1998; Saygin et al., 2012), bulk density (Reynolds et al., 2009), organic matter content (Gilley et al., 2001), available water capacity (Allen et al., 1998), *S* index (Dexter, 2004), among many others, have all been proposed as indicators of soil physical quality in some context.

The use of these properties as indicators of soil physical quality is implicitly empirical and has little to do with the description of soil physics given in the first paragraph of this introduction. Clearly, the "quality of the indicator" depends on its effectiveness in representing the attributes to which the robust model (read as "state of the art") indicates sensitivity.

An indicator that has received much attention, especially in Brazil, is the Least Limiting Water Range (Silva et al., 1994). It was introduced in Brazilian literature by Tormena et al. (1998) and translated to Portuguese as "Intervalo Hídrico Ótimo" (IHO). The Least Limiting Water Range (R_{LL}) is a mathematical proposition for the Non Limiting Water Range (NLWR), introduced by Letey (1985), who defined it as the range of soil water contents for which neither the matric potential nor aeration nor mechanical impedance would be limiting factors to the plants growth. In its conception and in the way it was introduced by Letey (1985), NLWR is a complex, comprehensive concept, to the extent that it comprises several aspects related to the soil physical conditions necessary for plant development. It does not, however, include hydraulic conductivity, closely associated with water availability (Gardner, 1960; Cowan, 1965), nor soil thermal properties, also influenced by the water content, which can determine plant growth (Abdelhafeez et al., 1975; Reddell et al., 1985). Silva et al. (1994) replaced the fundamentals of the NLWR soil-root interface processes by empirical limits of soil physical properties to establish a mathematical proposition for R_{LL}.

Similarly to what is seen for the *S* index proposed by Dexter (2004) and discussed by De Jong van Lier (2014), Brazil leads the world ranking in number of published research papers on R_{LL} (Gubiani et al., 2013a). This indicates a large number of human resources involved in determining the R_{LL}, and therefore not engaged in studying fundamental physical properties, how to model them, and, based on that, how to make sound predictions on the functioning of the soil-plant-atmosphere system. Aiming to investigate the scope of the information contained in the R_{LL} and its reliability to indicate "quality", upon which it was based, this work aims to analyze its limiting contents and compare them with basic soil physical properties. With this analysis, the authors invite students and researchers of soil physics to become acquainted with an objective interpretation of the R_{LL} and suggest a realignment of the soil physics research in Brazil with scientific precepts.

DEVELOPMENT

Definition of the indicator

The Least Limiting Water Range (R_{LL}, m^3 m^{-3}) is defined as:

$$R_{LL} = \max\,[0, \min\,(\theta_{fc}, \theta_{air}) - \max\,(\theta_{pwp}, \theta_{pr})] \qquad \text{Eq. 1}$$

where "max" represents the "maximum" function ($\max(i,j) = i$ if $i \geq j$; $\max(i,j) = j$ if $i<j$), and "min" is the "minimum" function ($\min(i,j) = i$ if $i \leq j$; $\min(i,j) = j$ if $i>j$). The definition of R_{LL} includes four limiting soil water contents, all on a volume base (m^3 m^{-3}): θ_{fc} is the water content at field capacity; θ_{air}, is the limiting water content for proper aeration; θ_{pwp} is the water content at the permanent wilting point; and $\theta_{pr,}$ is the soil water content corresponding to the limiting penetration resistance. The R_{LL} indicator can be compared to the quantity available water *A* (m^3 m^{-3}), defined as:

$$A = \max\,[0, \theta_{fc} - \theta_{pwp}] \qquad \text{Eq. 2}$$

Figure 1 shows the graphical representation of R_{LL} and *A,* according to equations 1 and 2 for the four possible combinations of the relative position of θ_{pwp} and θ_{pr} and of θ_{air} and θ_{fc}. *A* will be equal to R_{LL} in the case of $\theta_{pwp} \geq \theta_{pr}$ and $\theta_{fc} \leq \theta_{air}$ (case 1, Figure 1). In all other cases, R_{LL} will be smaller than *A*.

The limiting water contents, their coherence and parametrization

The limiting contents that comprise the R_{LL} definition (Equation 1) are:

- The field capacity limiting water content (θ_{fc}), defined by Veihmeyer and Hendrickson (1931) as "the amount of water held in the soil after the excess gravitational water has drained away and after the

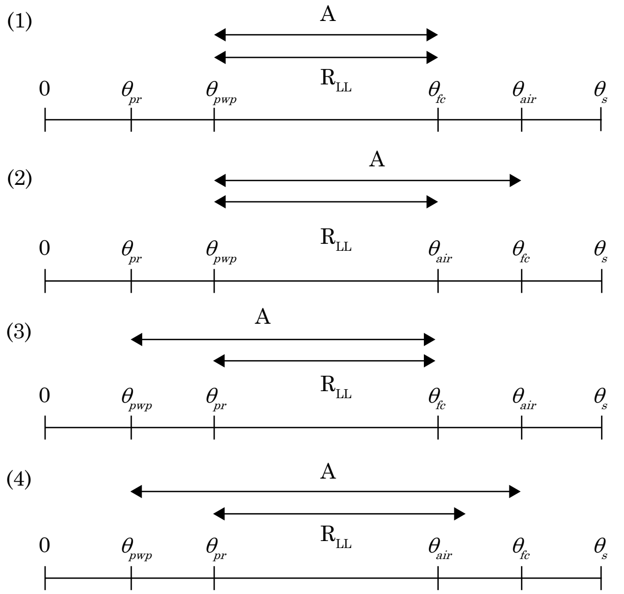

Figure 1. Least Limiting Water Range (R_{LL}) and available water (A) on a scale of volumetric water contents from completely dry (0) to saturation (θ_s), according to equations 1 and 2 for the four possible combinations of the relative position of water contents of permanent wilting and limiting root penetration resistance (θ_{pwp} and θ_{pr}) and of water contents of limiting air-filled porosity and field capacity (θ_{air} and θ_{fc}).

rate of downward movement of water has materially decreased, which usually takes place within 2 or 3 days in pervious soils of uniform structure and texture".

- The limiting water content for proper aeration (θ_{air}), which is the maximum water content corresponding to an air-filled porosity that allows an adequate exchange of gases between soil and atmosphere, ensuring that in any rooted portion of the soil there is no excess of CO_2 or lack of O_2. The crop stress associated with this parameter (if $\theta > \theta_{air}$) is the anoxic stress.
- The limiting water content corresponding to the permanent wilting point (θ_{pwp}), which delimits soil conditions in which a plant will permanently (that is, without recovery) wilt in short time. The stress associated with this parameter (if $\theta < \theta_{pwp}$) is the drought stress.
- The limiting water content related to excess root penetration resistance (θ_{pr}), representing the water content below which the plant roots cannot penetrate the soil for mechanical restrictions. The stress associated with this parameter (if $\theta < \theta_{pr}$) is the mechanical stress.

A cursory analysis of the limiting values that are used to define R_{LL} reveals some key aspects. Two of the limiting water contents, θ_{pwp} and θ_{pr}, represent conditions that correspond to the "fatal" limit of the respective stress - drought and mechanical (permanent wilting and zero root growth), while a third water content, θ_{air}, corresponds to the onset of the anoxic stress phase, when aeration conditions have just begun to cause damage to the plant, but below a fatal stress level. The three types of stress regarding their respective limiting contents are schematically represented in figure 2. In the example illustrated in this figure, there is a near-fatal stress condition (water content "1", where the water content is slightly above θ_{pwp}), which, nevertheless, is within the range considered as R_{LL}.

An opposite situation, i.e., water content outside the R_{LL}, but without causing stress to the plant, may occur when $\theta_{fc} < \theta_{air}$ (cases 1 and 3 of Figure 1) and when $\theta_{fc} < \theta < \theta_{air}$ (situation 2, Figure 2). In such conditions, the plant is not suffering any kind of stress, however, the corresponding water content is not included in the R_{LL}. Considering the definition of field capacity, water contents higher than θ_{fc} will rapidly decrease in time due to drainage, and θ_{fc} will be reached in a matter of days. Depending on rainfall and other boundary conditions, the amount of water taken up by the plant in the range of θ_{fc} and θ_{air}, when $\theta_{fc} < \theta_{air}$, may, nevertheless, be considerable.

In virtually all studies published in Brazil on the subject, the parametrization of the four limiting contents of the R_{LL} is fake and just consists of using a set of fixed values. For θ_{fc} a water content is used that corresponds to a given matric potential (-10 or -33 kPa, in general); θ_{air} is chosen to match the air content of 0.10 m^3 m^{-3}; θ_{pwp} is considered to correspond to the matric potential of -1,500 kPa; and θ_{pr} is chosen equivalent to the water content at which the soil has a predefined resistance to penetration (often 2 MPa). Except in some studies (Klein and Camara, 2007; Kaiser et al., 2009; Gubiani et al., 2013b), the values in general are not tested and compared with biological measurements, and a sensitivity analysis of the outcomes of studies regarding these values is rarely performed. In some cases, only the effect of the value chosen for penetration resistance in θ_{pr} is assessed (Betioli Júnior et al., 2012; Moreira et al., 2014b). The justification for using one or another set of values, if any, has been limited to quoting other publications in which the same values were used. The scientific flaw of doing so becomes clear when one realizes that the cited papers did, on their turn, not present sustainable justification; the values employed were chosen by someone at a certain moment, but their validity is much more the product of self-assertion than experimental scientific confirmation.

Moreover, few studies focus on the association of R_{LL} and crop response. Those who do show low

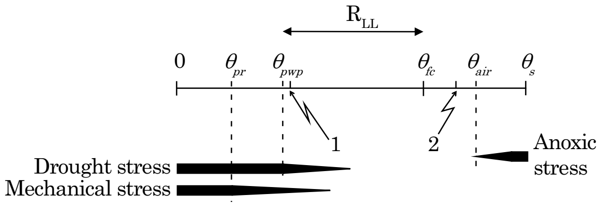

Figure 2. The Least Limiting Water Range (R_{LL}) corresponding to case 1 of figure 1, with indication of drought, mechanical and anoxic stresses. The water content indicated with 1 represents a water content within R_{LL} but with near-fatal stress, and water content 2 refers to a water content outside the R_{LL}, but without stress.

correlation, as found in a wide literature review (Gubiani et al., 2013a), as well as in an experimental corroboration with eight maize crop cycles (Gubiani et al., 2013b).

Such apparent contradiction - it would be reasonable to assume that an indicator of soil physical quality applied to agronomy would have correlation with yield - may have two main explanations. There may be a structural problem in the adopted model; in other words, the parameters considered or the way they are related to calculate the R_{LL} (Equation 1) are not sufficient to represent the processes that determine the crop yield. Alternatively, the calibration of the model may be wrong, i.e. the values attributed to the limiting contents are incorrect.

Taking into account that the parameters included in the calculation of R_{LL} can represent drought stress and anoxic stress, and also include mechanical root growth stress, the most likely explanation for the observed low correlation is the simple way by which the parameters are related in R_{LL} as well as inaccuracies in their calibration.

Limiting contents *versus* physical properties

In the following, we describe some relationships between the R_{LL} limiting water contents and primary soil physical properties that can be determined objectively.

The field capacity limiting water content *versus* hydraulic retention and conductivity

Field capacity, by definition, is related to the vertical water draining movement and, therefore, depends on the water flow through the soil profile. The water flow in porous media is described by the Darcy-Buckingham Law, which establishes that the water flux density is equal to the product of hydraulic conductivity and the total hydraulic gradient. This law, when combined with the mass conservation principle, results in the Richards Equation, allowing predictions on soil water conditions in time and space. In addition to information on the specific geometry of the problem, in order to apply the Richards Equation it is necessary to know the relationship between hydraulic conductivity (K), matric potential (h) and water content (θ). Such relationships are highly nonlinear and hysteretic, and describing them in a mathematical format allowing a relatively simple solution is still one of the challenges of soil physics.

The relation between soil water content or matric potential at field capacity and soil hydraulic properties may be assessed simulating an internal drainage experiment using a hydrologic model based on the Richards Equation. Following this approach, Twarakavi et al. (2009) used the *Hydrus* model (Simunek and van Genuchten, 2008) and estimated field capacity for a large number of soils, discussing the sensitivity of the determination to the soil hydraulic properties and the criterion of negligibility of the drainage rate to be adopted. These authors proposed the following empirical equation to estimate the water content at field capacity as a function of other soil physical parameters:

$$\theta_{fc} = \theta_r + (\theta_s - \theta_r)n^{0.60\log_{10}\left(\frac{q_{fc}}{K_s}\right)} \qquad \text{Eq. 3}$$

where θ_r, θ_s and n are parameters of the water retention equation by van Genuchten (1980); K_s is the saturated hydraulic conductivity and q_{fc} is the flux considered negligible for the purposes of field capacity estimation. In this equation, K_s and q_{fc} should be expressed in the same unit of time per length (TL^{-1}).

By combining equation 3 with the van Genuchten (1980) water retention equation, the following expression for the matric potential at field capacity is obtained:

$$h_{fc} = \frac{\left(n^{\frac{0.60n\log_{10}\left(\frac{q_{fc}}{K_s}\right)}{1-n}} - 1\right)^{\frac{1}{n}}}{\alpha} \qquad \text{Eq. 4}$$

In this equation, h_{fc} assumes the inverse unit of the α parameter from the van Genuchten (1980) equation. For example, if α is chosen in cm^{-1}, h_{fc} will be in cm. Twarakavi et al. (2009) concluded that the use of a "negligible" flux of $q_{fc} = 0.01$ cm d^{-1} resulted in good estimations of field capacity for a wide range of soils; and for this q_{fc} value, equations 3 and 4, for K_s in cm d^{-1}, become, respectively:

$$\theta_{fc} = \theta_r + (\theta_s - \theta_r)n^{-0.60(2+\log_{10}K_s)} \qquad \text{Eq. 5}$$

$$h_{fc} = \frac{\left(n^{\frac{0.60n(2+\log_{10}K_s)}{n-1}} - 1\right)^{\frac{1}{n}}}{\alpha} \qquad \text{Eq. 6}$$

Based on their studies, Twarakavi et al. (2009), similarly to Souza and Reichardt (1996), concluded that the use of a fixed value for the matric potential to estimate field capacity does not correspond to reality. Figure 3 shows the h_{fc} values as a function of the saturated hydraulic conductivity K_s, as calculated by equation 6 for soils with a = 0.015 cm^{-1} and for five values of parameter n. The figure illustrates the tendency that is intuitively perceived: higher K_s values result in quicker drainage, causing the soil to dry more (more negative matric potential) until reaching the draining rate that was pre-established as negligible.

The equation developed by Twarakavi et al. (2009) was included here just as an example. For its development a soil database was used that contains predominantly soils from temperate regions. Moreover, equation 4 does not allow the inclusion of vertical heterogeneity (stratification) of the soil, which, when it occurs, may have a major effect on the water content and on the matric potential corresponding to field capacity. It would not be possible to include such heterogeneity in a simple empirical equation like equation 4, because it would increase the number of parameters in such a way that a solution by regression, as obtained by Twarakavi et al. (2009), would become inviable. Moreover, applications to solve for the problem of multi-layer systems already exists, in the form of numerical hydrologic models based on the Richards Equation. One of these models (*Hydrus*) was used by Twarakavi et al. (2009) themselves and depends only on the hydraulic properties as a function of depth to calculate the flows.

The limiting water content corresponding to the permanent wilting point *versus* retention and hydraulic conductivity

The water content corresponding to the permanent wilting point (θ_{pwp}), by definition, refers to the lower limit of extractable soil water by plant roots. Its experimental determination is time-consuming and obtained values are discussed, e.g., by Haise et al. (1955), Veihmeyer and Hendrickson (1955) and Cutford et al. (1991). The soil water content can become lower than θ_{pwp} only by evaporation or drainage. Therefore, using θ_{pwp} to calculate crop available water A seems plausible, but its use in the R_{LL} definition, with the adjective *least limiting*, does not seem reasonable, as will be explained in the following.

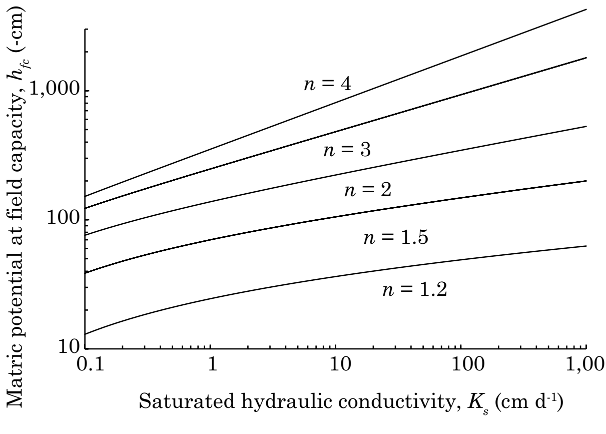

Figure 3. Matric potential corresponding to field capacity (h_{fc}) as a function of saturated hydraulic conductivity (K_s), according to Twarakavi et al. (2009) (Equation 6) considering a negligible bottom flux for the purpose of field capacity (q_{fc}) of 0.01 cm d^{-1}, for five van Genuchten (1980) soils (five values of shape factor n; shape factor α equal to 0.015 cm^{-1} in all cases).

The inclusion of θ_{pwp} in R_{LL} as the lower limit corresponding to drought stress represents a gross simplification of the existing knowledge on transpiration reduction due to soil drying, as observed in experiments like those reported by Meyer and Green (1980), Wright and Smith (1983), Casaroli et al. (2010) and many others. To improve the empirical modeling of this phenomenon, Doorenbos and Kassam (1986), Feddes et al. (1978, 1988) and van Genuchten (1987) developed mathematically simple proposals to describe the phenomenon, used in several hydrological models, such as *Hydrus* and *SWAP*. Lascano and van Bavel (1986), Jarvis (1989, 2011) and Li et al. (2001) offered relatively simple proposals that allow considering the soil vertical heterogeneity as well.

The permanent wilting water content θ_{pwp} is defined based on the process of water uptake by plant roots; to predict it, one should model the water flow towards the plant roots, which, in the same way as for $\theta_{fc,}$ can be done by means of the Richards equation with appropriate boundary conditions. Classical publications on the item are those by Gardner (1960) and Cowan (1965) who developed theories based on the Richards equation and basic theory of water extraction from the soil by the plants.

Numerical algorithms based on the theory by Gardner (1960) were presented in several recent publications (Javaux et al., 2008, 2013; De Jong van Lier et al., 2006, 2013; Couvreur et al., 2012). The plant root geometry and properties, specifically the limiting root (or leaf) water potential and internal plant resistances, together with the soil water potential and the hydraulic conductivity of the soil near the roots, determine whether a plant can or cannot withdraw water at rates compatible with the atmospheric demand, allowing the assessment of drought stress.

Consequently, regarding the lower limit for crop water availability, retention and hydraulic conductivity are the physical properties of major interest. De Jong van Lier et al. (2006, 2008) showed that the matric flux potential (M, m^2 d^{-1}) (Gardner, 1958; Raats, 1970; Pullan, 1990), a soil physical property that integrates retention and conductivity, is the physical parameter most directly linked to crop available water. M is defined as:

$$M = \int_{h_l}^{h} K(h)dh \qquad \text{Eq. 7}$$

where h_l is the limiting matric potential, the most negative value that the water in the roots can assume. By writing the Darcy equation in terms of M it is shown that the spatial gradient of M (dM/dx) is equal to the water flux density in the absence of gravitational flow, which, approximately, is the case for water uptake from the soil by plant roots.

When the *K(h)* function is known, the determination of *M(h)* is a matter of analytical or numerical integration. Figure 4 illustrates, for two differently textured soils, hydraulic conductivity *K* (Figure 4a) and its integral, the matric flux potential *M* (Figure 4b) as calculated by equation 7, as a function of the matric potential. For a given matric potential, the *M* value corresponds to the ease with which a plant withdraws water from the soil. Figure 4c shows the ratio of the *M* values of the two soils as a function of the matric potential. It can be seen that for not too negative matric potentials (wet soil), the relative difference between the *M* values for both soils is small, but for more negative matric potentials (drier soil) the *M* of the clay loam soil becomes orders of magnitude higher than in the sandy loam soil. This indicates a much higher availability of water in the clay loam soil.

The limiting water content for proper aeration *versus* gas diffusion

Soil aeration is the process through which the gases produced or consumed in soil are exchanged with the atmosphere, primarily by diffusion. The main gas consumed in the soil is oxygen, whereas the main gas produced is carbon dioxide. Thus, soil aerobic processes depend on the flow of O_2 from the atmosphere into the soil, and of CO_2 in the opposite direction. Diffusion of these gases is much higher in air than in water. So, the higher the soil water content the greater the difficulty for an adequate aeration, which can hinder plant growth and should be considered for the modeling of plant production.

By integrating various factors that control the aeration process in order to meet the biological demand, as described by De Jong van Lier (2001), De Jong van Lier and Cichota (2004) presented the following equation to estimate the minimum

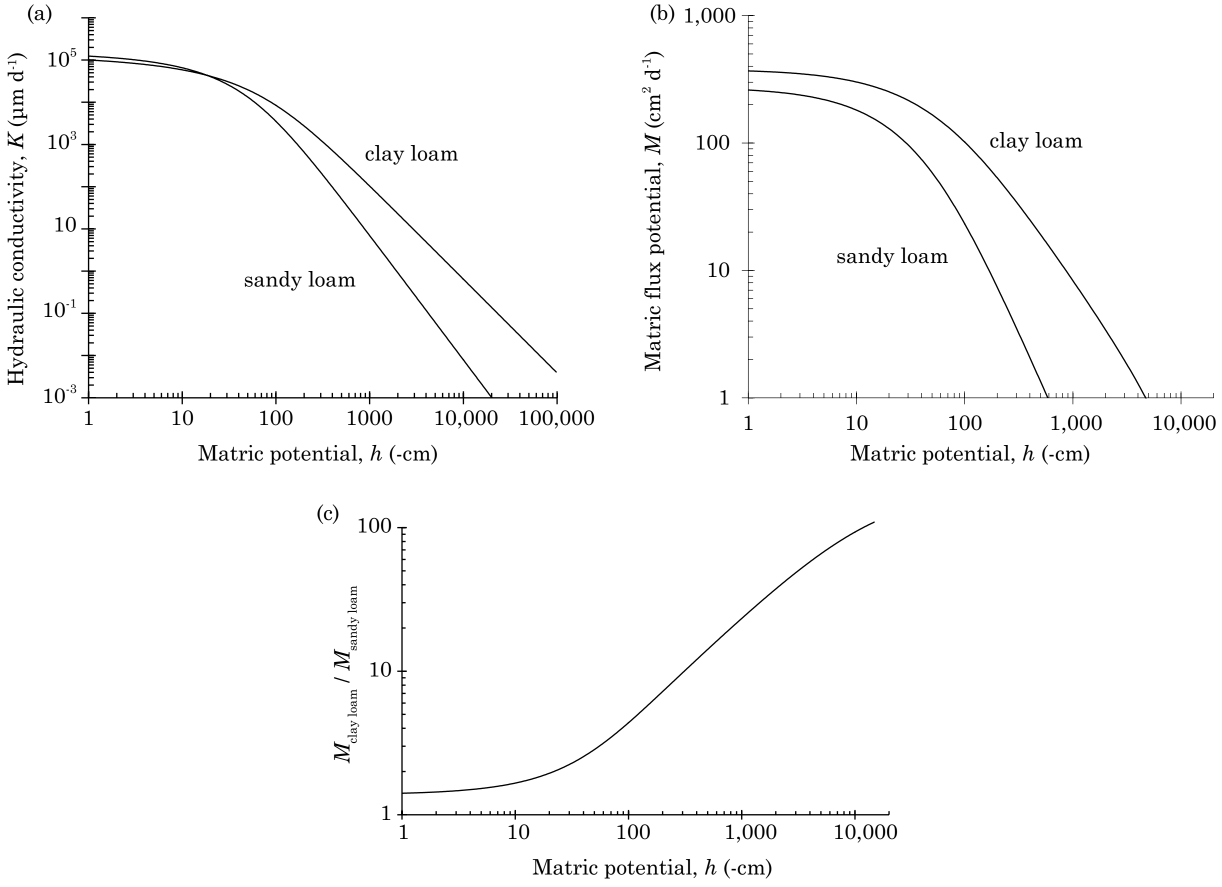

Figure 4. Hydraulic conductivity *K* (a), the matric flux potential *M* (b) (integral as calculated by equation 7, with h_l = -15,000 cm) as a function of the matric potential for two different soil textures and the ratio of the *M* values of both soils (c) as a function of the matric potential.

required aeration porosity as a function of the O_2 consumption in the soil, the depth and total porosity of soil, the O_2 content in the atmosphere and O_2 diffusion in the air:

$$\beta_{\min} = \left[\frac{S_{\max} Z^2 \chi^2}{([O_2]_{atm} - [O_2]_{\min}) D^a} \; \frac{p}{2p + 4}\right]^{3/10} \qquad \text{Eq. 8}$$

In this equation, β_{min} (m^3 m^{-3}) is the minimum aeration porosity necessary to ensure that no part of the plant root system will suffer from lack of oxygen; S_{max} (kg m^{-3} s^{-1}) is the oxygen consumption rate per unit of soil volume at the soil surface (S_{max} was considered as $28.2 \cdot 10^{-8}$ kg m^{-3} s^{-1}); Z(m) is the rooting depth; χ (m^3 m^{-3}) is total porosity (χ was considered equal to 0.5 m^3 m^{-3}); $[O_2]_{atm}$ (kg m^{-3}), the oxygen concentration in atmosphere, considered as 0.269 kg m^{-3}; $[O_2]_{min}$ (kg m^{-3}) is the minimum oxygen concentration to sustain life at a given soil depth (considered $[O_2]_{min}$ equal to $[O_2]_{atm}/4$); D^a (m^2 s^{-1}) is air diffusivity for oxygen ($D^a = 1.78 \cdot 10^{-5}$ m^2 s^{-1}); and p is a factor determining the shape of the function of O_2 consumption decrease with depth (S_{O2}, kg m^{-3} s^{-1}) (De Jong van Lier and Cichota, 2004), where S_{O2} is equal to S_{max} at the surface (z = 0) and zero when $z = Z$, according to:

$$S_{O_2} = S_{\max}\left[1 - \left(\frac{z}{Z}\right)^p\right] \qquad \text{Eq. 9}$$

Equation 8 was applied for rooting depths up to 1.0 m and for p-values of equation 9 that represent different oxygen consumption distributions with depth, from consumption concentrated at the soil surface (p=0.1) to a practically equal consumption at all depths occupied by the root system (p=10) (Figure 5). As a result, β_{min} ranged from 0.02 to 0.24 m^3 m^{-3}. This range could be enlarged considering other values for χ and S_{max}. It is worth noting that the β_{min} values, as calculated by equation 8 and represented in figure 5 refer to the minimum air content at the soil surface, through which all O_2 consumed and CO_2 produced in the soil profile is flowing. The greater the depth, the smaller the flow of O_2 and CO_2 and the smaller will be the content of air required for an adequate aeration. Clearly, the application of any fixed value for β_{min}, such as the value of 0.1 m^3 m^{-3} used for calculation of θ_{air} of R_{LL}, means failing to consider the complexity of the aeration process and believing that it is possible to infer biological consequences from a fixed fraction of soil porosity not occupied by water.

A more complete approach of the subject is presented by Bartholomeus et al. (2008), who modeled, besides the soil macroscopic diffusion, the microscopic oxygenation process of individual roots, and found β_{min} values varying from 0.02 and 0.08 m^3 m^{-3} for diverse scenarios, together with a high sensitivity for soil temperature and rooting depth. According to these authors, fixed values for β_{min} (such as the 0.1 m^3 m^{-3} value adopted in virtually all works involving R_{LL}) very unlikely will represent an approximate value of the actual value.

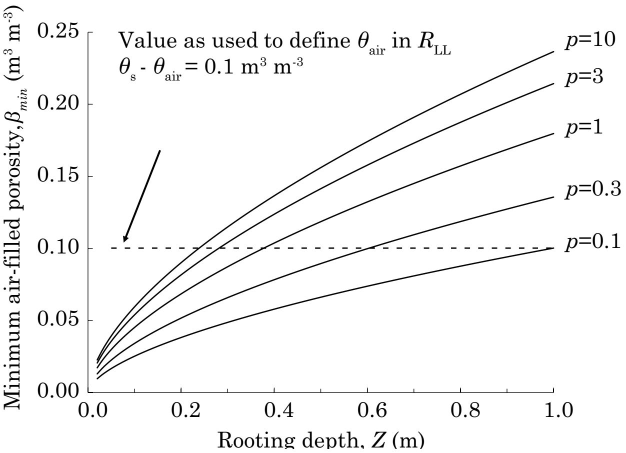

Figure 5. Minimum air-filled porosity for proper aeration β_{min} as a function of the empirical parameter p and depth of the root system Z, as calculated by equation 8.

The limiting water content related to penetration resistance *versus* the physics of root elongation

The resistance that solid particles in the soil apply against a motion or displacement results from complex relations of cohesive forces of solid-solid interactions, adhesive forces of solid-liquid interactions and frictional forces generated during displacement (Keller et al., 2013). When a root penetrates the pores of a soil, its growth will cause a significant displacement of the particles when it does not change its geometry to fit the irregular geometry of the pore space, when it forces its way through the pore cavity that it had filled or when pore space must be created (Bengough et al., 1997, 2006, 2011; Clark et al., 2003). Root growth can be considered a cell mass flow into the soil (cell division and elongation). Directing the cell flow to less resistant areas is a biological strategy to save the energy captured in the photosynthesis process.

The Lockhart's model (Lockhart, 1965; Jordan and Dumais, 2010), employed in plant physiology to study the force relations involved in cell elongation, considers that cell walls behave as a Bingham fluid. A Bingham fluid, as opposed to a Newtonian fluid, requires a minimum pressure σ_Y>0 to cause its deformation. The relative deformation rate over time will be proportional to the applied pressure σ (Pa) reduced by σ_Y (Pa):

$$\frac{1}{L}\frac{dL}{dt} = \mu[\sigma - \sigma_Y] \qquad \text{Eq. 10}$$

where L (m) represents the root length, t (s) is time, and the property μ (Pa^{-1} s^{-1}) is called extensibility. In the case of cell elongation, σ_Y can be understood as the cell wall resistance (R, Pa), i.e. the pressure at which the cell walls resist deformation. The cell turgor (T, Pa) is the internal cell pressure and is equivalent to the σ of equation 10 (Bengough et al., 1997). The difference between T and R is called net cell pressure (P_{lc}, Pa):

$$P_{lc} = T - R \qquad \text{Eq. 11}$$

By comparing equations 10 and 11, we see that P_{lc} represents the rate of deformation over time divided by its extensibility.

The soil mechanical resistance to root growth effectively occurs only when turgid roots exert pressure on the surrounding environment. In these cases a reaction pressure (P_{rs}) is produced by the soil, its value being limited to the soil mechanical impedance $P_{rs,max}$. The direction of the resulting force from such pressure in the cell wall is opposite to the force provided by the cell turgor pressure (P_{lc}). The roots continue growing and moving soil particles while $P_{lc}>P_{rs,max}$. Note that the presence of roots is indispensable for the existence of P_{rs}, but their presence alone is not sufficient, because those roots with $P_{lc}=0$ do not provide the required physical conditions for the occurrence of P_{rs}.

Quantification of the soil mechanical impedance can be achieved by using available types of penetrometers and measurement techniques, as discussed by Stolf (1991). In general, the soil mechanical impedance measured by penetrometers (R_P, Pa) is the quantification of the soil response to pressure, resulting from the reaction to the pressure caused by the penetration of a metal cone positioned at the end of a rod into the soil. Although R_P is useful to detect differences in soil resistance as a function of cohesive, adhesive or frictional forces and to distinguish pedological and tillage factors that affect such forces, it will not represent the manifestation of P_{rs}, given the physical conditions required for the occurrence of P_{rs} and because of the different scales and geometries of the cell expansion when compared to the penetrometer cone.

Because of the difficulty in determining $P_{rs,max}$, some researchers attempted to establish empirical relationships between R_P and the cell elongation rate dL/dt. In a recent literature review, some relationships were presented and discussed by Bengough et al. (2011). From their experiments it became evident that in order to obtain empirical relations a homogeneous soil matrix (samples prepared in laboratory) was a prerequisite, as well as matric potentials less negative than -0.5 to -0.1 MPa. In the same moist conditions, the expectation is that the relation between dL/dt and R_P will not be confirmed in cases where cracks and biopores are present, occupying a large portion of the soil volume (the plant directs the cell flow to less resistant spaces) which is common in conservation-tillage crop areas (Ehlers et al., 1983). For such areas and based on the criterion that there has not been a close relationship between some biological variable with R_P, some researchers suggest that critical R_P values should be higher than 2 MPa (Klein and Camara, 2007; Reichert et al., 2009; Moraes et al., 2014). However, the use of values above 2 MPa (e.g. 3.5 MPa as suggested by Moraes et al., 2014) often corresponds to matric potentials close to the permanent wilting point. In some cases of the study conducted by Moraes et al. (2014), R_P would reach 3.5 MPa only for matric potentials below the wilting point. In such conditions, P_{lc} and, consequently, P_{rs}, can be so small that the biological stress associated with the mechanical factor is negligible if compared to the stress associated with the drought factor. In these cases, interpreting the occurrence of loss in biological variables as caused by a high R_P means the incorrect attribution of the cause to the mechanical factor when it is essentially a lack of water.

The empirical relationships established between R_P and other soil properties, such as those used to estimate R_P as a function of bulk density (ρ) and water content [$R_P = f(\rho, \theta)$], and which constitute the mathematical sub-model of the limiting mechanical impedance often used in combination with the calculation of R_{LL}, are useful to represent the relationship between the soil properties included in the sub-model. However, such models of relationships between soil properties do not contain any information about the occurrence and magnitude of P_{rs}. Its use in the context of R_{LL} aiming to estimate θ_{pr} corresponding to a fixed R_P only informs that the mechanical reaction of soil to a metal rod, in terms of pressure, would be equal to the fixed R_P value. Assuming that the roots face this same resistance means accepting all interpretation errors of the cause factor and the conceptual errors previously mentioned.

Problems and mistakes in interpreting the R_{LL}

Interpretation of R_{LL} values is achieved by comparison. It is often concluded that the soil physical quality worsened when the R_{LL} decreased as a function of some agricultural tillage system or other factor. Such comparison usually includes an assessment of different scenarios. Changes in soil management, for example, represent changes in the plant root density, rooting depth, and soil hydraulic properties. At the same time, the R_{LL} in its original conception has limitations when the scenario presents more complex boundary conditions. Is it plausible to use fixed values for the limiting contents regardless of the phenological and pedological boundary conditions? The previous sections raised several arguments for a negative answer. So, would the calculated R_{LL} that disregards a change in the boundary conditions be valuable as a comparative indicator? Probably not, as previously discussed.

Then, how could the R_{LL} be used as an indicator? According to the previous discussion, it would be necessary to estimate the limiting contents considering the changing boundary conditions. This process would be as complex, or even more complex, than the use of a detailed mechanistic model and, therefore, the advantage of R_{LL} being a "simple" indicator would disappear.

Regarding the upper limit of the R_{LL}, the inconsistencies in the choice of θ_{air} or θ_{fc} as limiting values have already been discussed. For the lower limit, it was observed that θ_{pwp} corresponds to a condition of total drought stress, which would better be replaced by a value corresponding to a considerable stress, but not total, or, in analogy to what is done in the case of θ_{air}, to the water content corresponding to the onset of drought stress. The relationship between drought stress and matric potential is discussed in detail by Metselaar and De Jong van Lier (2007) and by De Jong van Lier et al. (2009). The theory presented in these publications shows that drought stress, quantified by relative transpiration, increases in a nonlinear way when the matric potential decreases from a certain value, generally in the range of -30 to -100 kPa (Kukal et al., 2005; Liu et al., 2012), much less negative than the permanent wilting point. Thus, the use of a water content corresponding to this order of magnitude of potential (critical water content, θ_{cr}) to replace θ_{pwp} in the calculation of the R_{LL} sounds reasonable and was proposed yet recently by Silva et al. (2015). Their data show that, as a consequence, the permanence of θ_{pr} in the R_{LL} calculation would be superfluous, once its value, in almost all situations, would be lower than θ_{cr}. This finding corroborates with the fact that the major models of plant growth do not use, among their input data, information on the penetration resistance, and yet they result in good predictions. Apparently, the process (plant growth) is not sensitive to parameters that relate penetration resistance to water content.

Two boundary conditions, common in numerous production systems, will be discussed in the following sections. The first refers to the phenology of the crop under observation; the second, to variations in soil properties with depth. For neither of them R_{LL} can be easily introduced as an indicator.

Phenological boundary conditions and their consequences for the R_{LL}

During crop development, plants undergo a series of phenological changes that affect the transfer of mass and energy in the soil-plant-atmosphere system. The most obvious parameters include changes in the rooting depth, distribution and growth, leaf area index, carbohydrate partitioning among plant organs and other physiological parameters. Hydrological models, when coupled to plants growth models, usually treat these parameters as a function of time, development stage or accumulated heat sum. For the purpose of R_{LL}, interpretation would be achieved based on the limiting contents that, except for θ_{fc}, which is exclusively related to soil, should be considered as variable during crop development.

As the rooting depth and root length density increase, β_{min} increases and the corresponding θ_{air} decreases. Thus, for the first phenological stage, the required air-filled porosity is very low and θ_{air} becomes virtually equal to θ_s; at the peak of root growth, according to the theory presented, β_{min} can represent half of the total porosity (Figure 5). The great variation of these values during the cycle of an annual crop shows that the use of a R_{LL} with fixed limiting values is not consistent with the real conditions in this context either.

Regarding θ_{pr}, in the reproductive stage root growth becomes irrelevant. Hence, in this phenological stage, the mechanical resistance is no longer biologically important, θ_{pr} equals zero, and the expression to calculate R_{LL} (Equation 1) could be reduced to:

$$R_{LL} = \max\,[0, \min\,(\theta_{fc}, \theta_{air}) - \theta_{pwp}] \qquad \text{Eq. 12}$$

This fact is important, for example, when assessing the correlation between grain productivity and R_{LL}, which may show a significant reduction of R_{LL} if θ_{pr} is the lower limit of R_{LL} and $\theta_{pwp}<\theta<\theta_{pr}$, but this reduction is not correlated to dry matter accumulation during the reproductive phase.

The value of θ_{pwp} (or the critical water content θ_{cr} that might replace it) should also be dependent on crop phenology. As previously discussed, θ_{pwp} is influenced by the root system's ability to withdraw a sufficient amount of water from the soil to meet the transpiration demand. The transpiration demand is determined, among other factors, by the leaf area index, which is dependent on development stage. Simultaneous with an increase in leaf area, the root system also grows in depth and density. The combined effect of these factors should be considered for an accurate determination of the value of θ_{pwp} or θ_{cr}.

Pedological boundary conditions and their consequences for the R_{LL}

Most soils present morphological stratification. The distribution of the root system in the soil, with a density that normally decreases with depth, superposes this pedological stratification. Consequently, the rate at which plant roots take up water from the soil is not uniform with depth, and as soil water redistribution is a slow process, water content variations between depths will arise. Thus, one can expect that the values of the several limiting water contents, regardless of how they are estimated, vary with depth. Taking the R_{LL}

indicator, its definition is applicable to only one soil horizon, however, scenarios in which the conditions of one horizon are outside the R_{LL}, while another horizon is within R_{LL} may be supposed to occur frequently. In these cases, the indicator does not allow a unique prediction. To what extent would the favorable conditions in one horizon compensate the unfavorable conditions in another one?

Considering available water A, the integration of its value along the rooted soil depth z_e (m) results in the available water capacity C_{AW} (m):

$$C_{AW} = \int_0^{z_e} A dz \qquad \text{Eq. 13}$$

A similar integration could be proposed for the R_{LL}, but it would not make much sense once the purpose of R_{LL} is its use as an indicator of soil quality. A simple integration, as in the case of C_{AW}, would disregard any compensatory effect that may exist when one soil horizon is outside the optimum range and another one is within it.

Critical density

Very common in publications addressing the least limiting water range is its estimation for several soil densities or degrees of compaction, aiming to predict the effects of a possible compaction on the soil physical quality and crop yields (Imhoff et al., 2001; Leão et al., 2004; Beutler et al., 2008; Blainski et al., 2009; Kaiser et al., 2009; Petean et al., 2010; De Lima et al., 2012; Farias et al., 2013; Guimarães et al., 2013; Moreira et al., 2014a; Seben Junior et al., 2014). In this case, θ_{fc} and θ_{pwp} are usually estimated as a function of an empirical relationship between the water content, bulk density and matric potential proposed by Silva et al. (1994) or other also empirical equations (Guimarães et al., 2013), using fixed values for the matric potential; θ_{pr} is calculated as a function of soil bulk density using the empirical model proposed by Busscher (1990), assessing it for a fixed impedance value, commonly 2 MPa; and θ_{air} is calculated by subtracting 0.1 $m^3 m^{-3}$ from total porosity, which is a function of the bulk and particle density.

The results are usually presented in the form of a graph of the four limiting water content values, where the abscissa represents the soil bulk density and the ordinate represents the water content, as exemplified in figure 6. In this context, “critical bulk density” is defined as the lowest soil density for which the R_{LL} equals zero. For such bulk density, or higher values, irrespective of the water content in the soil, it would be outside the R_{LL}, and, therefore, productivities in such soils would always be reduced.

The described procedure is emblematic for the shift of attention that resulted from the introduction of the R_{LL} in Brazilian scientific circles. The processes and mechanisms that govern the system are not discussed. Instead, conclusions are based on the perfection attributed to the indicator. To its value, obtained by extrapolation of experimental observations using empirical relationships, predictive qualities and recommendations on soil management to establish required bulk densities are attributed. However, it is clear that, in case of soil compaction (a decrease in total porosity, particularly in macroporosity), there are predictable changes for almost all soil physical properties. Such changes will influence the R_{LL} limiting contents in an equally predictable manner, as exemplified by the dotted lines in figure 6 and detailed as follows:

a. The saturated or near-saturated hydraulic conductivity decreases as macroporosity decreases. Hence, the draining process slows down, and the water content at field capacity (dependent on the negligibility criterion) will correspond to a less negative matric potential (wetter soil) than for the same non-compacted soil, as also discussed in the context of the equation 6 developed by Twarakavi et al. (2009).

b. By reducing total porosity, according to De Jong van Lier (2001) and Bartholomeus et al. (2008), the minimum air-filled porosity is expected to decrease. Taking into account that compaction is likely to cause a reduction of the root growth as well as of the depth of the soil explored by the root system, the minimum air-filled porosity would be even more reduced. For example, using the values presented by De Jong van Lier (2010) for high oxygen consumption conditions, if total porosity decreases from 0.6 to 0.5 $m^3 m^{-3}$ and the depth of the root system decreases from 0.5 to 0.4 m, the minimum air-filled porosity would decrease from 0.17 to 0.13 $m^3 m^{-3}$.

c. Compaction reduces the soil hydraulic conductivity at high water contents, but increases the hydraulic conductivity under drier conditions (Hillel, 2003). Thus, in drier soils, access to water will be easier in compressed soil, and the matric potential corresponding to θ_{pwp} or θ_{cr} is expected to decrease (become more negative).

These predictable facts show the non-validity of fixed values of air content and matric potentials for calculation of the R_{LL} limiting contents when the objective is to compare its value before and after a compaction. As R_{LL} assessment is always made with fixed values to assess the limiting levels, whereas the existing knowledge indicates that such levels should change because of compaction, the reliability of the critical densities found by this estimation method is, at least, questionable.

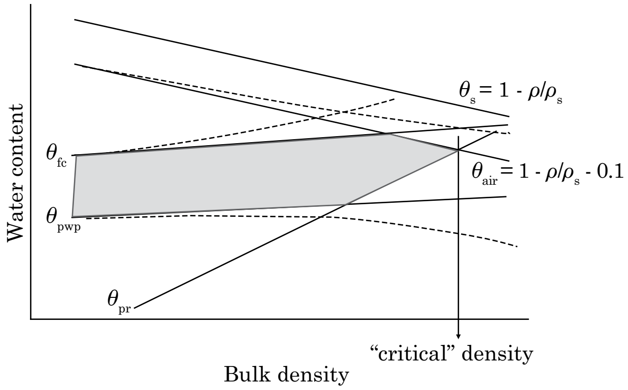

Figure 6. Representation of R_{LL} limiting water contents *versus* bulk density. Solid lines represent the limiting water contents of R_{LL} estimated based on fixed parameters; dotted lines show the expected behavior of the limiting water contents based on physical knowledge. The gray colored area represents the R_{LL} integral over the range of represented densities. θ_{pwp} θ_{fc}, θ_{air}, θ_{rp}: water water contents corresponding to permanent wilting, field capacity, limiting air-filled porosity and limiting penetration resistance, ρ: bulk density, ρ_s: particle density.

FINAL CONSIDERATIONS

Considering the availability of robust models for agronomy, ecology, hydrology, meteorology and other related areas, the appeal of the R_{LL} as an indicator in Brazilian soil physics cannot be assumed for its effectiveness, never proven, but should be explained by the simplicity with which it is dealt. The exercise of estimating the limiting water contents in the light of the state of the art of soil physics, instead of considering them a function of simple constants, proves to be as or more complex than the existing mechanistic models. The amount and extent of objective information contained in the R_{LL} limiting contents, when based on constants, is minimal when compared to the amount of objective information contained in continuous functions of properties of biological and physical processes. Thus, the great disadvantage of using the R_{LL} as an indicator compared to the use of models that integrate such functions based on mechanistic knowledge becomes evident. The R_{LL} is a mathematical model, but a sensitivity analysis of R_{LL} to the limiting values was only performed in one of the first publications on the subject (Silva et al., 1994). Since then, what has been done as an approximation of calibration is not much more than verifying the dependence between R_{LL} and the soil bulk density. The few tests of the correlation between R_{LL} and crop yields, as described by Gubiani et al. (2013a), in most cases refuted it, as also reported by Gubiani et al. (2013b). Further research conducted with the purpose of revealing the relationship between R_{LL} and soil bulk density or compaction, without questioning the limiting values or testing the sensitivity of R_{LL} to these values will not add knowledge and should be discouraged. Research on R_{LL} can provide scientific contribution, but should inform in which circumstance R_{LL} is a reliable indicator of the soil physical quality for plant production by comparing plant variables with water content in the context of R_{LL}.

CONCLUSIONS

The four limiting contents of the R_{LL} are related to crop yield. However, their determination using fixed values of air content, matric potentials and mechanical impedance of soil marginalizes the existing knowledge in the field of soil physics, plant physiology and agrometeorology.

When calculated using the limiting water content for the onset of drought stress instead of the permanent wilting point, R_{LL} shows insensitive to parameters that relate penetration resistance to water content. This corroborates to the fact that major crop growth and yield prediction models do not include soil mechanical information among their input parameters, and suggests that the determination of these parameters in the context of soil water availability and crop growth is counterproductive.

The search for quantifying concepts such as the least limiting water range R_{LL} goes against the systemic understanding, being restricted to the simple determination of the respective limiting values, relegating the study or concern with the actual functioning of the system to a secondary role. Contrary to more complex models, indicators such as the R_{LL}, with fixed limiting values as most researchers use them, show no correlation with crop productivity.

In the light of such findings, the attention given to the R_{LL} in Brazilian soil physics is not justified. The authors of this study suggest a realignment of the research in Brazilian soil physics with the scientific principles towards emphasizing mechanistic soil physics rather than the search for empirical correlations far below the state of the art of soil physics.

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