



# Integral water capacity (IWC) and least limiting water range (LLWR): prediction using plant growth indices and soil properties

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## Abstract

Soil water availability is an important field of study in soil water and plant relationship. Least limiting water range (LLWR) and integral water capacity (IWC) are two important concepts which are used for water availability to plant. LLWR is determined from four moisture coefficients ( $\theta_{AFP}$ ,  $\theta_{FC}$ ,  $\theta_{SR}$ ,  $\theta_{PWP}$ ) that are the soil water contents 10% air-filled porosity (AFP), at field water capacity (FC), 2 MPa penetration resistance (SR), and permanent wilting point (PWP), respectively. The computation is dependent on critical values, so IWC was introduced to avoid using the critical limits that sharply rises in a cut-off from 0 to 1 at the wet end of water release curve or sharply falls from 1 to 0 at the dry side in the previous concepts of water availability for plant. IWC is the integral of differential water capacity function ( $C(h)$ ) in the amplitude of 0 to infinity soil matric potential ( $h$ ) multiplied by some weighting functions ( $\omega_i(h)$ ) each considering the effect of various soil limitations on water availability to plants. Up to now, the effect of different soil attributes and the tillage treatments have been reviewed on LLWR. The effect of soil various physical and chemical limitations such as soil hydraulic conductivity ( $K(h)$ ), aeration, SR, and salinity has been considered on IWC computation. LLWR and especially IWC have been seldom studied using plant real response. Results of few studies about LLWR and IWC using stomatal conductance and canopy temperature showed that their values were considerably different with those computed based on previously introduced critical limits for LLWR and weighting functions for IWC. These differences indicate that the critical limits proposed by da Silva et al. (Soil Sci Soc Am J 58:1775–1781, 1994) and weighting functions by Groenevelt et al. (Aust J Soil Res 39:577–598, 2001) may not be applied indiscriminately for all plants and should to be modified according to plant response. Physiological characteristics like transpiration and photosynthesis rate, chlorophyll index, leaf water potential, and relative water content also could be appropriate indices for monitoring plant water status and computation the real value of LLWR and IWC in the field or greenhouse for various types of plants.

**Keywords** Moisture coefficients · Weighting functions · Physiological characteristics

## Introduction

According to the classic definition for soil available water to plants, plant available water (PAW), imagined, and described between SWC at field capacity (FC) and permanent wilting point (PWP) (Veihmeyer and Hendrickson 1927, 1931) based on soil water potential (Kirkham 2004) and maximum plant growth is possible when the matric potential ( $h$ ) of soil water is equivalent to FC (100–330 cm). When soil water potential reduces from its threshold value, plant growth and yield reduce. The SWC between FC and the threshold value is known as readily available water (RAW). In this definition it is assumed that in the range of RAW, there is no limiting factor for plant growth in the soil, but in this range, soil aeration and soil penetration resistance (SR) may be limiting for

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plant growth. Therefore, non-limiting water range (NLWR) concept was introduced by Letey (1985), at which soil water content, aeration, and SR are not limiting for plant growth. In this definition, only  $h$ , aeration, and SR were considered, while the possible influence of environmental conditions on the growth of plants can limit water availability for plants. da Silva et al. (1994) developed and introduced least limiting water range (LLWR) instead of NLWR. LLWR is the range of SWC where restrictions by soil aeration, water potential and SR are least for plant growth. da Silva et al. (1994), used critical values for computation of LLWR (SR 2 MPa and air-filled porosity (AFP) of 10%). Groenevelt et al. (2001), presented the integral water capacity (IWC) concept that is not dependent on critical boundary values or constants. Groenevelt et al. (2001) developed weighting coefficients,  $\omega_i(h)$ , that continuously can be utilized to a wide range of soil water potential (from 0 to 15,000 cm or even beyond) which takes into account various limiting factors restricting soil water availability within that range. The objective of introducing IWC, a superior alternative to PAW, NLWR, and LLWR, was to avoid using the weighting functions that sharply increasing from 0 to 1 at the wet end of water release curve (WRC) or decreasing from 1 to 0 at the dry side. Up to now, many researchers have been worked on the influence of soil properties including clay content (%C) (da Silva et al. 1994; Tormena et al. 1999; Fidalski et al. 2010; Neyshabouri et al. 2014), organic carbon (OC), (da Silva et al. 1994; Fidalski et al. 2010; Neyshabouri et al. 2014), metal oxides (citrate–bicarbonate–dithionate extractable iron and aluminum ( $Fe_d$  and  $Al_d$ ), ammonium oxalate extractable manganese and iron ( $Mn_o$  and  $Fe_o$ ) and calcium carbonate equivalent (CCE) (Neyshabouri et al. 2014), and soil management or various tillage practices effect (Olibone et al. 2010; Perez and de Andreu 2013; Guedes et al. 2014; Chen et al. 2015; Kahlon and Chawla 2017; de Souza et al. 2017; Haghighi et al. 2017) or it is in the form of soil compaction or  $D_b$  (da Silva et al. 1994; Zou et al. 2000; Leão et al. 2005; Fidalski et al. 2010; de Lima et al. 2015). Moreover, Kazemi et al. (2018) computed its value using the plant response (leaf stomatal conductance,  $g_s$ ). Many researchers have computed IWC using soil properties by Groenevelt et al. (2001) method (Asgarzadeh et al. 2010) and plant response (Neyshabouri et al. 2018). Groenevelt and Grant (2004) and Grant et al. (2010) investigated the influence of soil salinity on IWC using soil properties and Meskini-Vishkaee et al. (2018) using soil and plant properties. It seems that there is a need to consider the type of plant, its particular needs or behaviors, and environmental conditions in addition to soil condition in computing water availability for plant.

Water deficiency significantly affects photosynthetic characteristics (Guo et al. 2018; Iqbal et al. 2019) and plant physiology (Brestic and Zivcak 2013). Due to climate change, water shortage and temperature extremes remarkably affect

the both terrestrial and aquatic ecosystem production (Islam et al. 2019; Baiazidi-Aghdam et al. 2016). Water scarcity causes a decrease in the plant water potential (Dodd et al. 2008; Dauda et al. 2019; Brestic and Zivcak 2013), leaf stomatal conductance, and, consequently, transpiration rate (Farooq et al. 2009; Brestic and Zivcak 2013), photosynthesis, cell proliferation and plant growth (Lawlor and Tezara 2009; Brestic and Zivcak 2013; Wu et al. 2018). Water stress leads to oxidative stress and a reduction in photosynthetic properties (Petrov et al. 2018; Iqbal et al. 2019). Abscisic acid (ABA), proline, mannitol, sorbitol, and components like glutathione and ascorbate accumulate in the plant (Yordanov et al. 2003). Chlorophyll fluorescence measurements are an indicator of different drought responses of photosynthesis (Brestic and Zivcak 2013). Chlorophyll fluorescence properties are an index to determination the quantum yield of photosystem II under water-deficiency condition (Batra et al. 2014). Photosynthesis is meaningfully influenced by water stress, because it inhibits the energy transportation from photosystem II to photosystem I (Siddique et al. 2016). It also reduces the palisade of spongy tissues and ultimate leaf thickness so results in lower values of chlorophyll fluorescence (Brestic and Zivcak 2013; Wang et al. 2018). Water stress also significantly reduces the leaf relative water content (RWC) (Farooq et al. 2009; Xavier et al. 2019) and disrupts the semi-permeability of cell membranes and, consequently, increases the leakage of cytosolic solutes (Petrov et al. 2018). The effect of water deficiency on soluble protein, proline, Rubisco activity (RA), and enzymatic activities is also investigated by many researchers for various plants (Iqbal et al. 2019). Soluble protein, proline, Rubisco activity (RA), and enzymatic activities are investigated by many researchers for various plants (Iqbal et al. 2019). Advances in remote sensing and infrared radiometry have enabled the canopy temperature at the field level to be used as an indicator of water stress to monitor water availability (González-Dugo et al. 2006). Since 1980, leaf temperature measurements in plants have been increasingly considered as an indicator of stress status, based on the fact that transpiration causes leaf cooling (Bazzaz et al. 2015). As the available water content decreases, stomatal conductance and transpiration decrease and leaf temperature increases. In fact, plants with poor water status have higher canopy temperatures than ambient temperatures (Buttar et al. 2005). Up to now, LLWR or IWC is seldom studied for plants under water deficiency using plant physiology and morphology, while computing these concepts for water availability using plant indices like transpiration and photosynthesis rate, chlorophyll index, stomatal conductance, canopy temperature, or other mentioned physiological parameters could led to obtaining real values than using some previously constant critical limits (for example 2 MPa for SR or 10% for AFP for LLWR) or theoretically weighting functions for IWC. In

this paper, we have tried to consider the studies about LLWR and IWC, and give a view to provide better and real results using plant physiological characteristics.

## LLWR

An amplitude of soil water content, where soil physical conditions are the least constrained in terms of aeration, SR, and  $h$  for water supply to the plant, is expressed by LLWR) (da Silva et al. 1994; de Souza et al. 2017). Furthermore, using the LLWR has been suggested as a potential crop production index (Benjamin et al. 2003; da Silva and Kay 2004), soil structural quality index (da Silva et al. 1994; de Lima et al. 2015) and to evaluate management systems (Kay et al. 2006; Ramos et al. 2015). LLWR has been defined by da Silva et al. (1994) on the base of non-limiting water range (NLWR) concept that has been presented by Letey (1985). A large amount of LLWR indicates that soil is more resistant to limitations caused by the environmental condition including soil aeration restriction, SR, and water deficiency. A small value of LLWR indicates that plants grown in a given soil may be more sensitive to the mentioned limitations, and this soil may have a low productivity (Neyshabouri et al. 2014). LLWR is computed from four moisture coefficients including soil water content at 10% AFP ( $\theta_{AFP}$ ), at field water capacity ( $\theta_{FC}$ , soil water content at matric potential equal to 0.01 MPa (da Silva et al. 1994)], water content at SR equal to 2 MPa ( $\theta_{SR}$ ), and at permanent wilting point ( $\theta_{PWP}$ ) (soil matric potentials equal to 1.5 MPa, respectively).  $\theta_{AFP}$  or  $\theta_{FC}$  is presumably the upper limit of the LLWR ( $\theta_{UL}$ ) according to whether soil rapid drainage or aeration is limiting for water availability.  $\theta_{SR}$  or  $\theta_{PWP}$  is assumed to be the lower limit ( $\theta_{LL}$ ) according to whether SR or soil water condition limits water availability for plant (da Silva et al. 1994). For the computation of LLWR, we need to determine the relations between soil matric potential ( $h$ ), SR and soil aeration with SWC ( $\theta$ ). The relation between SWC and soil matric potential is water retention curve (WRC) that can be described by several models including van Genuchten model (1980) Kosugi (1994), da Silva and Kay (1996), Fredlund and Xing (1994) and Groenevelt and Grant (2004). da Silva et al. (1994) also suggested a power-form model for WRC (Eq. 1) and used  $D_b$  as an effective factor on  $\theta$  and  $h$  relation.

SR is also usually impressed by  $\theta$  and  $D_b$ . The relationship between  $\theta$  and  $D_b$  as independent variables and SR as a dependent variable has been identified as soil penetration resistance curve (SRC) (Busscher 1990). The  $\theta_{SR}$  is defined as soil water content at the critical value for root growth (SR equal to 2 MPa). At SR values more than 2 MPa, plant growth is restricted (da Silva et al. 1994). There is an adverse relation between  $\theta$  and AFP, and soil aeration condition could be determined using their relation (da Silva et al. 1994; Neyshabouri

et al. 2014). Several pedotransfer functions (PTFs) have been suggested to predict WRC and SRC by applying soil bulk density ( $D_b$ ), organic carbon (OC), and clay content (da Silva et al. 1994; Fidalski et al. 2010). Some other researchers (Neyshabouri et al. 2014; Kahlon and Chawla 2017) have evaluated the effect of some other soil properties and management treatments (tillage treatments) on LLWR. The wide amplitude of LLWR indicates that soil LLWR is less susceptible to environmental stresses, inappropriate aeration, and high penetration resistance, and also indicates it is capable of producing high water yield (compared to soil with smaller values) (da Silva and Kay 2004). Some studies' results have shown that that soil management systems that lead to smaller LLWRs cause the plant to become more frequently exposed to stress due to scarcity or excessive water (aeration problem) (da Silva and Kay 1996). Tillage management operations affect the LLWR and consequently crop production capability (Iqbal et al. 2005) by affecting SR and soil hydrological properties (Shaver et al. 2002).

## Prediction of LLWR using pedotransfer functions

Prediction of LLWR to specify the influence of soil attributes may be accelerated through PTFs that explain WRC and SRC (da Silva et al. 1994; Neyshabouri et al. 2014; Fidalski et al. 2010). PTFs may turn to be an alternative to direct measurement. PTFs are a series of mathematical functions that predict or determine WRC and SRC curves based on soil attributes that can be easily and rapidly measured (Wagente et al. 1991). da Silva and Kay (1996) used the Ross et al. (1991) (Eq. 1) and Busscher (1990) (Eq. 3) for WRC and SRC models, respectively. da Silva et al. (1994) used multiple regression analyses to determine the effect of particle-size distribution (PSD), OC,  $D_b$ , and tillage on the coefficients of WRC ( $a$ ,  $b$ ) and SRC ( $c$ ,  $d$ ,  $e$ ) using Eqs. 5, 6 and 7–9 respectively:

$$\theta = \alpha\psi^b. \quad (1)$$

And its linear form could be written as:

$$\ln \theta = \ln \alpha + b + \ln \psi, \quad (2)$$

$$SR = c\theta^d D_b^e. \quad (3)$$

And its linear form could be written as:

$$\ln SR = \ln c + d \ln \theta + e \ln D_b^e. \quad (4)$$

da Silva et al. (1994) created the following PTFs for prediction of WRC and SRC coefficients:

$$\ln \alpha = -4.1518 + 0.6851 \ln \text{CLAY} + 0.4025 \ln \text{OC} + 0.2731 \ln D_b \quad (5)$$

$$b = -0.5456 + 0.1127 \ln \text{CLAY} + 0.0233 \ln \text{OC} + 0.1013 \ln D_b \quad (6)$$

$$\ln c = -3.6733 - 0.1447\text{CLAY} + 0.7653\text{OC} \quad (7)$$

$$d = -0.4805 - 0.1239\text{CLAY} + 0.2080\text{OC} \quad (8)$$

$$e = 3.8521 + 0.0963 \text{CLAY}. \quad (9)$$

Having these PTFs they computed the four moisture coefficients ( $\theta_{\text{AFP}}$ ,  $\theta_{\text{FC}}$ ,  $\theta_{\text{SR}}$ ,  $\theta_{\text{PWP}}$ ) and finally LLWR as follows:

$$\theta_{\text{AFP}} \geq \theta_{\text{FC}}, \theta_{\text{SR}} \leq \theta_{\text{PWP}} \quad \text{LLWR} = \theta_{\text{FC}} - \theta_{\text{PWP}} = \text{AWC} \quad (10)$$

$$\theta_{\text{AFP}} \geq \theta_{\text{FC}}, \theta_{\text{SR}} \geq \theta_{\text{PWP}} \quad \text{LLWR} = \theta_{\text{FC}} - \theta_{\text{SR}} \quad (11)$$

$$\theta_{\text{AFP}} \leq \theta_{\text{FC}}, \theta_{\text{SR}} \leq \theta_{\text{PWP}} \quad \text{LLWR} = \theta_{\text{AFP}} - \theta_{\text{PWP}} \quad (12)$$

$$\theta_{\text{AFP}} \leq \theta_{\text{FC}}, \theta_{\text{SR}} \geq \theta_{\text{PWP}} \quad \text{LLWR} = \theta_{\text{AFP}} - \theta_{\text{SR}}. \quad (13)$$

Neyshabouri et al. (2014) evaluated the relative effect of clay content, SAR,  $D_b$ , cation-exchange capacity (CEC), and soil cementing agents including calcium carbonate equivalent (CCE), citrate–bicarbonate–dithionate extractable iron and aluminum oxides ( $\text{Fe}_d$  and  $\text{Al}_d$ ), ammonium oxalate extractable iron and manganese oxides ( $\text{Fe}_o$  and  $\text{Mn}_o$ ), and OC on  $\theta_{\text{AFP}}$ ,  $\theta_{\text{FC}}$ ,  $\theta_{\text{SR}}$ ,  $\theta_{\text{PWP}}$ , and LLWR and created appropriate PTFs for their prediction from soil variables, using 188 undisturbed soil samples from 32 soils. The results showed the relative effect of

soil variables on LLWR,  $\theta_{\text{AFP}}$ ,  $\theta_{\text{FC}}$ ,  $\theta_{\text{SR}}$ ,  $\theta_{\text{PWP}}$ , and on  $\theta_{\text{SR}}$  was not similar. Among studied soil properties  $D_b$ ,  $\text{Fe}_o$  and clay content had a significant effect on LLWR ( $R^2 = 0.31$ ,  $p < 0.01$ ) (Neyshabouri et al. 2014). When studied undisturbed soil cores were grouped according to clay content or  $D_b$ , the acquired PTFs for LLWR had more accuracy ( $R^2 = 0.76$  and  $0.86$ , respectively) compared to the condition which all cores were considered in a single group ( $R^2 = 0.31$ ) (Tables 1). In cores with the  $D_b$  equal and more than  $1.4 \text{ Mg m}^{-3}$ , first clay content and second  $\text{Al}_d$  (as a cementing agent) were the most effective soil variables on LLWR according to standardized regression coefficients. Calcium carbonate equivalent (CCE) was not appeared in the LLWR PTF (Table 1). The moisture coefficients of  $\theta_{\text{FC}}$  and  $\theta_{\text{PWP}}$  were affected by SAR significantly ( $P < 0.01$ ), but its effect on LLWR became insignificant (Table 1).

Kazemi et al. (2016) evaluated the performance of the several pedotransfer functions developed by applying multivariate linear regression (MLR), multi-objective group method of data handling (mGMDH), and artificial neural networks (ANNs) in the prediction of LLWR. Laboratory measurements in 188 undisturbed soil samples with the wide range of properties were used to compute four moisture coefficients ( $\theta_{\text{AFP}}$ ,  $\theta_{\text{FC}}$ ,  $\theta_{\text{SR}}$ ,  $\theta_{\text{PWP}}$ ) from which experimental LLWR ( $\text{LLWR}_e$ ) was computed. Eleven various soil attributes were also measured in disturbed samples and employed as independent variables to predict and LLWR (designated as  $\text{LLWR}_i$ ) and the same moisture coefficients by MLR mGMDH and ANNs methods. LLWR was also

**Table 1** Soil variables, standardized ( $b'$ ), and ordinary regression coefficients ( $b$ ) for the developed PTFs for prediction of  $\text{LLWR}_d$  for four soil groups

Soil variables and groups	Standardized regression coefficients ( $b'$ )				Ordinary regression coefficients ( $b$ )			
	$C < 20\%$	$C \geq 20\%$	$D_b < 1.4$	$D_b \geq 1.4$	$C < 20\%$	$C \geq 20\%$	$D_b < 1.4$	$D_b \geq 1.4$
	1	2	3	4	1	2	3	4
$a_0$	–	–	–	–	0.085**	– 0.365**	0.273**	0.789**
$\text{Al}_d$	– 0.382**	0.352**	–	– 0.492**	– $1 \times 10^{-4}$ **	$1 \times 10^{-4}$ **	–	– 0.001**
CCE	–	–	– 0.229**	–	–	–	– 0.001**	–
CEC	0.305**	– 0.367**	–	–	0.001**	– $2 \times 10^{-3}$ **	–	–
Clay	0.325**	0.254**	–	– 0.588**	0.004**	0.003**	–	0.005**
$D_b$	–	– 0.881**	– 0.244**	– 0.482**	–	– 0.317**	– 0.093**	– 0.411**
$\text{Fe}_d$	–	0.243**	–	–	–	$1 \times 10^{-5}$ **	–	–
$\text{Fe}_o$	–	–	–	–	–	–	–	–
$\text{Mn}_o$	–	0.117**	0.174*	0.363**	–	$2 \times 10^{-5}$ **	$2 \times 10^{-5}$ *	$2 \times 10^{-4}$ **
OC	0.390**	–	–	0.504**	0.019**	–	–	0.037**
SAR	–	–	–	–	–	–	–	–
$R^2$	0.35**	0.76**	0.15*	0.86**	–	–	–	–

– variable was not effective on LLWR

\*Significant at  $p < 0.05$

\*\*Significant at  $p < 0.01$



predicted directly ( $LLWR_d$ ) from the soil characters. Accuracy and reliability of the developed PTFs to predict  $LLWR_d$  and  $LLWR_i$ , as compared to the  $LLWR_e$ , were evaluated by applying relative improvement, Akaike information criterion, and root-mean-square error. ANNs predicted  $LLWR_d$  and  $LLWR_i$  most accurately and reliably; mGMDH and MLR ranked in descending order. Results showed that both indices were significantly improved from MLR to mGMDH and ANNs, but between mGMDH and ANNs, they were only significant at the training step. For  $LLWR_i$ , it was significant for validation step and  $LLWR_d$  was better correlated to  $LLWR_e$  (as a reference) than  $LLWR_i$ .

## The effect of soil properties on LLWR

### Soil texture

Topp et al. (1994) applied the normalized LLWR ( $LLWR/AWC$ ) to eliminate the influence of soil texture on LLWR. AWC is only affected by soil texture, while LLWR is influenced by both soil texture and structure. Therefore, the normalized LLWR ( $LLWR/AWC$ ) is a more useful indicator for soil structure, and yet, the correlation coefficients showed that the normalization process did not eliminate the influence of soil components on the LLWR. Clay content has a negative effect on  $LLWR/AWC$ . Also, these researchers obtained the correlation coefficients of  $-0.69$ , between normalized LLWR and clay content.

da Silva et al. (1994) expressed the strongest effect of clay percent on WRC than other soil particles (sand and silt). This finding contradicted the results of previous research by Ahuja et al. (1985) and Saxton et al. (1986) which reported that the clay and silt were associated with soil water retention. Clay percent had a nonlinear effect on  $\ln \theta$ . Regression analyses also showed that SR was correlated with clay with  $R^2 = 0.86$ . The effect of soil texture on  $\ln SR$  was only dependent on the change in soil clay content and may also be related to the close correlation coefficients between the soil particles (da Silva et al. 1994). Regardless of the  $D_b$ , least limiting water rang of the soil decreased with increasing clay content. This finding was inconsistent with da Silva et al. (1994) research that studied the effect of soil texture (as a soil structure index) on LLWR in two soils with silt loam and loamy sand texture classes. Their results showed that in silt loam, soil increasing  $D_b$  caused a decrease in  $\theta_{FC}$  and  $\theta_{PWP}$ .  $\theta_{AFP}$  has also decreased and was set as the  $\theta_{UL}$  instead of  $\theta_{FC}$  at  $D_b$  values equal and more than  $1.35 \text{ Mg m}^{-3}$ . Increasing  $D_b$  also caused an increase in  $\theta_{SR}$  and its substitution as the lower limit of LLWR at  $D_b$  values equal and greater than  $1.37 \text{ Mg m}^{-3}$ . As well as, with increasing soil  $D_b$ ,  $\theta_{UL}$  and  $\theta_{LL}$  intersected each other at  $D_b$  equal to  $1.56 \text{ Mg m}^{-3}$  ( $LLWR = 0$ ). In loamy sand soil with increasing soil  $D_b$ ,  $\theta_{FC}$  and  $\theta_{PWP}$  were increased, but

the increase in  $\theta_{SR}$  was higher than  $\theta_{PWP}$ . As a result, at  $D_b$  values higher than  $1.44 \text{ Mg m}^{-3}$ ,  $\theta_{SR}$  became the lower limit of LLWR. According to the soil texture, it had not aeration problem and  $\theta_{UL}$  was  $\theta_{FC}$  in all  $D_b$  range.

Tormena et al. (1999) proposed LLWR as an index of soil structural properties for crop production. In the study of these researchers, LLWR was affected by OC,  $D_b$ , and clay content, and plant growth was positively and significantly correlated with LLWR and negatively correlated with soil water abundance outside the LLWR range. They reported the value of LLWR in Eutrustox clay soil equal to  $0.118 \text{ cm}^3 \text{ cm}^{-3}$ , which was lower than that reported in medium-textured soils studied by da Silva et al. (1994), indicating that soil texture had a negative effect on LLWR (Beutler et al. 2005). This is due to the oxidative nature of the minerals present in the Eutrustox soil in comparison to the Haplustox soil, resulted in the formation of a very strong structure containing a lot of pores (Ferreira et al. 1999).

### Soil compaction and tillage treatments and management

Zou et al. (2000) examined the influence of soil compaction on LLWR in several forest soils to determine its effectiveness as a soil physical index. Soils with different textures including pumice (loamy sand,  $D_b = 0.7\text{--}0.85 \text{ Mg m}^{-3}$ ), Argillite (loam,  $D_b = 0.9\text{--}1.1 \text{ Mg m}^{-3}$ ), ash (sandy clay loam,  $D_b = 0.7\text{--}0.85 \text{ Mg m}^{-3}$ ), and a soil derived from loess sediments (silty clay,  $D_b = 0.85\text{--}1.05 \text{ Mg m}^{-3}$ ) were studied. Increasing soil bulk density, as an indicator of soil compaction, decreased LLWR. It was decreased when  $D_b$  of pumice and loess soils increased to high bulk values. While in the pumice with coarse texture and loess with fine texture, when the  $D_b$  increased from low to medium, LLWR was increased. LLWR increase in the pumice soil was due to the reduction of macropores, which increased the mesopores of soil. The rate of LLWR increase in the loess soil was the slowest due to the increase in SR in the medium texture soil (Zou et al. 2000). As well as, their results showed that all textures and  $D_b$  data showed a significant correlation with soil volumetric water content ( $R^2 > 0.93$ ). In medium-textured soils (Argillite and ash), increasing the  $D_b$  decreased LLWR in agree with the results of da Silva et al. (1994). Whereas in coarse-grained pumice soil, the medium  $D_b$  caused the LLWR to slightly increase. Because the organic matter (OM) causes the water content at FC to increases more than PWP. In soil derived from sediments with  $D_b$  of  $0.7 \text{ Mg m}^{-3}$ , there was no soil aeration and penetration resistance limitation and LLWR was equal to AWC. The following changes were observed when  $D_b$  reached  $0.8 \text{ Mg cm}^{-3}$  with a slight increase in soil compaction: (1)  $\theta_{AFP}$  was reduced, but the upper limit of LLWR was still  $\theta_{FC}$  and, therefore, did not influence LLWR, (2)  $\theta_{FC}$  increased, (3)  $\theta_{PWP}$  also increased, (4) there was a significant increase in soil SR as the soil penetration

resistance moved quickly toward high values of soil water content, but was still below  $\theta_{PWP}$ . At  $D_b = 0.85 \text{ Mg cm}^{-3}$ ,  $\theta_{SR}$  was more than  $\theta_{PWP}$  and became the lower limit of LLWR instead of  $\theta_{PWP}$ . This trend was similar in soils with different textures. Soil compaction reduced the LLWR in most cases. In coarse-grained pumice soil, the initial increase in soil bulk density increased LLWR due to the reduction of macropores and the increase in mesopores. Further increase in soil  $D_b$  resulted in a decrease in LLWR. However, with increasing soil compaction and  $D_b$  of aeolian sediments, the LLWR increased because as the  $D_b$  in the fine-textured soils increased, the increase in  $\theta_{SR}$  was less than  $\theta_{FC}$  (Zou et al. 2000).

Beutler et al. (2005) investigated SR and LLWR amplitude for soybean yield in a medium-textured oxisol (Haplustox) from Brazil. Their studies showed that soybean yield started to decline at  $D_b$  and SR values of  $1.48 \text{ Mg m}^{-3}$  and  $0.85 \text{ MPa}$ , respectively. The LLWR in the upper limit was limited by  $\theta_{FC}$  (soil water content at  $h$  of  $0.01 \text{ MPa}$ ) and the lower limit by the water content at the critical SR ( $SR_c$ ) obtained at the critical  $D_b$  of  $1.48 \text{ Mg m}^{-3}$ . Plant height decreased linearly from SR equal to  $1.46 \text{ MPa}$  and plant aerial part dry matter and the number of pods per plant from SR equal to  $0.39 \text{ MPa}$ . However, Beutler and Centurion (2003) found under greenhouse conditions at soil moisture content maintained in  $0.01 \text{ MPa}$  soil suction. There was a decrease in dry weight of soybean aerial part in two Haplustox and Eustrustox at penetration resistance of  $2.12$  and  $2.69 \text{ MPa}$ , respectively.

Different types of tillage treatments might improve soil physical attributes depending on cropping history, type of soil, climatic conditions, and previous tillage system. Tillage treatments affect the LLWR. This effect can be studied by the changes that these treatments make on  $D_b$  and the amount of soil organic matter (SOM). The  $D_b$  is a physical property of the soil associated with crop production, because it affects the relationships of soil, water, aeration, temperature, and SR (Ferrars et al. 2002). LLWR has been suggested as a potential crop production index (Benjamin et al. 2003; da Silva and Kay 2004) and soil structural quality index (Da Silva et al. 1994; Van Lier and Gubiani 2015; de lima et al. 2015), as well as at the farm scale to evaluate management systems (Kay et al. 2006; Ramos et al. 2015). LLWR has been reported by various researchers (da Silva et al. 1994; Klein and Camara 2007; Benjamin et al. 2014) as a useful soil physical quality index for plants, soils, and different types of tillage and soil managements.

da Silva and Kay (1997) investigated the position of soil (row, inter-row) and weather conditions in a clay loam, silt, and sandy loam soil in two no-tillage (NT) and conventional tillage (CT) systems on LLWR. They have reported that these two systems do not directly affect LLWR, but indirectly have an effect on OC and soil  $D_b$  and, consequently,

can affect the WRC and SRC; therefore, their effect on the LLWR was indirect. LLWR equal to zero occurred when  $\theta_{AFP}$  was equal to  $\theta_{SR}$  that represented the soil  $D_b$  at which LLWR was equal to zero (da Silva and Kay (1997).

Betz et al. (1998) applied the concept of LLWR as a function of  $D_b$  to study the effects of tillage and agricultural machinery traffic on rooting and the hydrological environment in a clay loam soil with poor drained condition as follows: (1) soil depth of  $5\text{--}10 \text{ cm}$  in no tracked and tracked inter rows of long-time tillage treatments including moldboard plow (MB), (NT) and chisel plow (CH); and (2) a plow pan at the depth of  $25\text{--}30 \text{ cm}$ . WRC and SRC were susceptible to tracking and to CH versus MB system, with  $R^2 > 0.70$ . Tracking in the NT system and compaction in the plow pan reduced the effect of  $D_b$  on the SRC about 75%. In CH and NT systems, tracking decreased the LLWR as much as  $0.04$  to  $0.06 \text{ m}^3 \text{ m}^{-3}$ . This decrease was smaller than  $0.02 \text{ m}^3 \text{ m}^{-3}$  for MB treatment. In the plow pan and NT systems,  $\theta_{SR}$  was the lower limit of LLWR in a wide range than  $\theta_{PWP}$ , exception for tillage systems with yearly tillage. Also, the soil non-appropriate drainage condition was more restrictive in two recent treatments than the CH and MB systems. The LLWR showed a significant soil structural effect on plant rooting. Soil hydraulic attributes related to the LLWR indicated soil aeration problem and high SR values created by conservation tillage system. It could be related to surface penetration of tillage equipment in soil.

Tormena et al. (1999) studied the physical properties of an oxisol soil under NT and CT plowing systems based on LLWR. The results showed that at  $D_b$  values less than  $1.02 \text{ Mg m}^{-3}$ , LLWR was positively correlated with  $D_b$ , and in the CT system, LLWR was higher than NT. At  $D_b$  greater than  $1.02 \text{ Mg m}^{-3}$ , the  $D_b$  correlation with LLWR was negative and its value in NT system was higher than that for CT.  $\theta_{LL}$  was  $\theta_{SR}$  in most of the soils in the CNT system. LLWR was  $0.18 \text{ cm}^3 \text{ cm}^{-3}$  in the low  $D_b$  ( $1.17 \text{ Mg m}^{-3}$ ) and  $0.09 \text{ cm}^3 \text{ cm}^{-3}$  in the high  $D_b$  ( $1.32 \text{ Mg m}^{-3}$ ) and in the NT system was  $0.16$  and  $0.6 \text{ cm}^3 \text{ cm}^{-3}$ , respectively, for high and low  $D_b$ s. For the CNT system, the critical LLWR occurred at  $D_b$  equal to  $1.46 \text{ Mg m}^{-3}$  with the assumption of  $SR_c$  equal to  $2 \text{ MPa}$  and at  $1.53 \text{ Mg m}^{-3}$  when  $SR_c$  was considered  $3 \text{ MPa}$ . For NT culture system, these values were  $1.53$  and  $1.54 \text{ Mg m}^{-3}$ , respectively. It seemed excessive tillage and vegetation cover on the soil surface in the CT system has caused rapid drying, so their SR has been increased abruptly and, consequently, the LLWR has been decreased. The mean LLWR was  $0.079 \text{ cm}^3 \text{ cm}^{-3}$  for NT and  $0.096 \text{ cm}^3 \text{ cm}^{-3}$  for CT systems.  $\theta_{LL}$  was  $\theta_{SR}$  for 46 and 89% of the studied soils in CT and NT systems, respectively.

Benjamin et al. (2003) stated that the coefficient of determination between wheat yield and LLWR was  $0.76$ , but LLWR was a poor index of plant productivity when the low SWC was limiting for crop production. Rechert et al. (2004)

determined the value of  $D_b$  and LLWR for four management systems including NT for 12 years, ChT (chisel tillage) of prior NT, and CT of prior NT on a sandy loam Hapludalf and related it to yield of bean and the number of days that SWC was out of the LLWR. For the 5 cm depth,  $D_b$  value was 1.72, 1.65, and 1.52  $\text{Mg m}^{-3}$  for NT, ChT, and CT, respectively. In NT system, the SR value for 6–10 cm soil depth was greater than 2 MPa, from 30 days next to beans seeding up to the end of the beans cycle. The number of days at which SWC for plant was out of the LLWR was 18, 13, and 19 days for NT, ChT, and CT, respectively. Differences among yield of beans for the studied tillage systems were not significant, showing that the number of days that SWC was out of the LLWR could not affect the yield of beans. Although, da Silva and Kay (1997) showed that the number of the days that SWC was outside the LLWR affected corn plant growth negatively. The correlation between corn plant growth and LLWR was positive.

Lapen et al. (2004) examined the changes of four soil moisture coefficients, which are the basis of LLWR computation, due to plowing and the number of trafficking machines for corn (*Zea mays* L.) establishment and yield. The results showed that untilled plots had lower AFP and lower oxygen concentration than the tilled and well-managed plots and concluded that the lower the AFP, the lower corn yield, SR was not a limiting factor in their study.

Leão et al. (2006) used LLWR as an index of changes in physical properties of the surface soil after converting the grasslands to short-term grazing (SG) and continuous grazing (CG) systems and reported that, in SG system, LLWR was most limiting for root growth compared to CG. However, the whole soil  $D_b$  amplitude was under the critical bulk density ( $D_{bc}$ ). In NC system, physical limitations for root growth were the minimum and soil  $D_b$  was smaller than  $D_{bc}$  and LLWR was equal to classic plant available water ( $\theta_{FC} - \theta_{PWP}$ ) for 96% of soil bulk density range. For CG system,  $\theta_{SR}$  was as  $\theta_{LL}$  in 70% of soil bulk density range, which indicates that SR was a limiting factor in this system. In SG system,  $\theta_{SR}$  was the lower limit of LLWR for all range of  $D_b$  and it stayed under  $D_{bc}$  ( $1.41 \text{ Mg m}^{-3}$ ) for 40% of  $D_b$  range in that system. The LLWR demonstrated to be a good soil physical quality index in the current study, being susceptible to changes in the surface soil physical attributes. In addition, Leão et al. (2005) reported that in  $D_b \geq D_{bzero}$ , soil physical condition for root development became very inappropriate, and generally, its main reason was structural degradation and soil compaction.

Olibone et al. (2010) studied the influences of crop rotation and chiseling on LLWR of the soil, as a soil physical characteristic to a depth of 0.1 m and crop yields under NT on a tropical Alfisol in Brazil, for 3 years. Crop rotation and plant residues on the soil can increase the soil water retention capacity that may be expressed in the form of LLWR

concept. Soybean and corn were grown in the summer in rotation with pearl millet (*Pennisetum glaucum*, Linne, cv. ADR 300), grain sorghum (*Sorghum bicolor*, L., Moench), congo grass (*Brachiaria ruziziensis*, Germain et Evrard), and castor bean (*Ricinus comunis*, Linne) during fall/winter and spring, under NT or chiseling. LLWR was computed after drying the cover crops and before planting soybean. In upper layers of soils with NT system without initial chiseling, soil physical and hydraulic properties got better. In seasons that water shortage was not intensively limiting, soil compaction did not restrict yield of the crop, whereas dry matter yield of cover crops was maximum in a dry season that Congo grass cropped alone or intercropped with castor bean. The yield of soybean did not reply to alterations in the LLWR. As a result, crop rotations may improve LLWR in the cultivable layer of the soil (0.1 m), but LLWR could not predict the influences on the yields of crop under dryness conditions (Olibone et al. 2010).

Perez and de Andreu (2013) carried out soil physical degradation which was the main problem which impressed the soil quality for crops production in agricultural soils in Venezuela. They have determined the LLWR and its reply to structural changes on studied soils. The soils were planted with corn plant under various tillage systems (NT, CT, and CT-follow) and non-planted under the native forest. PTFs relating the SRC, WRC with PSD, OC, and  $D_b$  were developed and used to compute the LLWR. Results showed that soil physical degradation under CT and high clay content had the highest negative effect on the LLWR. For silty clay loam soil, the LLWR was narrower, because the upper and lower limits of the LLWR became  $\theta_{AFP}$  and  $\theta_{SR}$ , respectively, indicating the aeration and high penetration resistance problems in the studied soil. In contrast, for sandy loam soil that was non-degraded with high sand content, the LLWR showed the highest values that the upper and lower limits of LLWR associated with  $\theta_{FC}$  and  $\theta_{PWP}$ , respectively. For loam and silty loam soils, the LLWR declined with increasing clay content and  $D_b$ , and then, its upper and lower limits were  $\theta_{FC}$  and  $\theta_{SR}$ , respectively. In 41% of the soils,  $\theta_{SR}$  became the lower limit of LLWR, and in 94% of them,  $\theta_{FC}$  was the upper limit of LLWR.

Guedes et al. (2014) reported that physical quality of the soil seedbed influences germination, seedling emergence, and crop establishment, which determined the LLWR of a soil seedbed cultivated for 18 consecutive years under NT, submitted to mechanical chiseling (NT-M) and biological chiseling by a forage radish cover crop (NT-B) in Brazil. At 5–10 cm soil depth, the NT-M treatment showed the lowest  $D_b$  ( $\approx 1.22 \text{ Mg m}^{-3}$ ) at the first sampling (2009), whereas NT-B system showed the highest  $D_b$  ( $\approx 1.2 \text{ Mg m}^{-3}$ ) at the second sampling (2010). However,  $D_b$  did not vary among treatments at the depth of 0–5 cm for both appraisal periods. SR was the most limiting factor of the LLWR,

which was greater in NT-M system for both soil layers at the first sampling. At the second sampling, the NT treatment had the highest LLWR at 0–5 cm depth, but at soil depth of 5–10 cm, NT-M and NT systems had greater LLWR than NT-B system. The usefulness of mechanical chiseling in improving soil seedbed physical quality lasted 18 months after its application. Biological chiseling was efficient only in improving soil AFP in both periods.

Klein and Klein (2015) determined the amount of LLWR in NT ( $D_b = 1.28 \text{ Mg m}^{-3}$ ) and CNT (no-tillage chiseled) ( $D_b = 1.24 \text{ Mg m}^{-3}$ ) cultivars in a Hapludox soil and examined their relationship with maize grain yield. These researchers observed that the amount of LLWR and the number of days that the SWC was within the LLWR range were higher in the NT conditions, and the maize yield was also higher ( $11.81 \text{ Mg ha}^{-1}$  against  $12.42 \text{ Mg ha}^{-1}$  for NT and CNT systems, respectively) that was due to the decreased soil compaction by chiseling. In areas with NT system and the traffic of agricultural machinery, soil degradation (Tavares et al. 2001) resulted in some problems in soil structure like increasing  $D_b$ , reducing soil porosity and infiltration and finally yield (Modolo et al. 2008). Soil disruption causes a decrease in root penetration resistance (Veiga et al. 2007), soil  $D_b$  (Klein and Camara 2007), increasing total porosity (da Silva Junior et al. 2010), soil hydraulic conductivity ( $K(h)$  water infiltration rate (Camara and Klein, 2005), macropores (Klein et al. 2008), and decreasing micropores ( $< 0.0002 \text{ mm}$ ). In the research of Klein and Klein (2015) in the NT system, at  $D_b$  equal to  $1.05 \text{ Mg m}^{-3}$ , SR was 2 MPa, and in the  $D_b$  equal to  $1.20 \text{ Mg m}^{-3}$ , it was 3 MPa. In the CNT system, these SR values occurred in  $D_{bs}$  of 1.15 and  $1.25 \text{ Mg m}^{-3}$ , respectively.  $\theta_{FC}$  became the upper limit of the LLWR and in lower  $D_{bs}$ ,  $\theta_{PWP}$  was the lower limit.  $\theta_{SR}$  was set as LLWR lower limit in higher values of soil  $D_b$ .

de Lima et al.'s (2015) study showed the range of LLWR was limited by the  $\theta_{FC}$  and  $\theta_{SR}$ . LLWR values ranged from 0.00 to  $0.14 \text{ m}^3 \text{ m}^{-3}$  for alfisol and  $0.00\text{--}0.04 \text{ m}^3 \text{ m}^{-3}$  for oxisol, respectively. The critical value of  $D_b$  for crop production was 1.79 and  $1.35 \text{ Mg m}^{-3}$  and a critical degree of compactness (DC) was 96 and 74% for alfisol and oxisol, respectively.

Chen et al. (2015) studied on a prior study of tillage treatments, which this research showed the effect of LLWR as an index of SOC mineralization under various tillage systems (NT and mouldboard plowing (MP) in black soil of North-east China in 2009. A study was carried to investigate the relation between LLWR, which was computed based on soil  $D_b$  and PSD. In opposition to MP, NT had a significantly higher volume of large macropores ( $> 100 \mu\text{m}$ ) at depths of 0–0.05 and 0.2–0.3 m, but a significantly lower volume of small macropores (30–100  $\mu\text{m}$ ) at depths of 0–0.05, 0.05–0.1, 0.1–0.2, and 0.2–0.3 m. The volumes of mesopores (0.2–30  $\mu\text{m}$ ) and micropores ( $< 0.2 \mu\text{m}$ ) at various depths

under the two tillage systems were similar. Tillage-induced variations in soil  $D_b$  and pore-size volumes influenced the ability of soil to fulfill necessary soil functions in conjunction with the OM turnover. Soil pore-size distribution, particularly small macropores, hugely impressed LLWR and there was a significant correlation between LLWR (which was computed based on soil  $D_b$ ) and the ratio of small macropores. The ratio of small macropores was used to compute LLWR instead of soil  $D_b$ , and the values of LLWR for NT and MP soils ranged from 0.073 to  $0.148 \text{ m}^3 \text{ m}^{-3}$ . Using the ratio of small macropores rather than  $D_b$  in the computation of LLWR resulted in more sensitive indications of SOC mineralization (Chen et al. 2015).

Haghighi et al. (2017) determined the LLWR for various soil management systems in dryland farming in Iran for four tillage treatments including NT, CT, reduced tillage (RT), and fallow no-tillage (NT<sub>f</sub>). Furthermore, LLWR was specified for control soils, compacted soils, plowed compacted soils, and control soils with super absorbent polymers' (SAPs) application. WRC, SRC, AFP, and  $D_b$  were specified for the 0–5 and 0–25 cm depths. Mean LLWR ( $0.07\text{--}0.08 \text{ cm}^3 \text{ cm}^{-3}$ ) was lower in compacted soils than the soils under CT, NT, NT<sub>f</sub>, RT, tilled, control, and SAP practices, but it was not different among tillage practices. The values of LLWR were  $0.12 \text{ cm}^3 \text{ cm}^{-3}$  for NT and CT. In compacted soils, LLWR became 0.77 times smaller than tilled plots. Analysis of the upper and lower limits of the least limiting water showed that the aeration problem did not restrict water uptake and SR was the only restricting parameter (Haghighi et al. 2017).

Kahlon and Chawla (2017) studied the effect of tillage practices [CT, NT (no-tillage without residue), NTR (no-tillage with residue), and DT (deep tillage)] on LLWR in North-west India. The highest value of mean LLWR was found in DT ( $0.26 \text{ m}^3 \text{ m}^{-3}$ ) and lowest in NT ( $0.15 \text{ m}^3 \text{ m}^{-3}$ ).  $\theta_{FC}$  was the upper limit of the LLWR beyond  $D_b = 1.41 \text{ Mg m}^{-3}$  and, after that,  $\theta_{AFP}$  was an important factor. However, for the lower limit of it, the  $\theta_{PWP}$  was limiting factor beyond  $D_b = 1.50 \text{ Mg m}^{-3}$ . Thereafter,  $\theta_{SR}$  become the lower limit of LLWR. Thus, DT under compaction and NTR under water stress were appropriate practices for acquiring maximum crop and water productivity. DT to 45 cm soil reduced the amount of  $D_b$  by 8%. In the experiment of these researchers, maximum  $D_b$  content was recorded in NT and NTR in the 15–30 cm ( $1.76 \text{ Mg m}^{-3}$ ) and 0–15 ( $1.57 \text{ Mg m}^{-3}$ ) layers. Therefore, high  $D_b$  may be created in the hardpans created by CT operations and the use of heavy machinery at a constant depth.

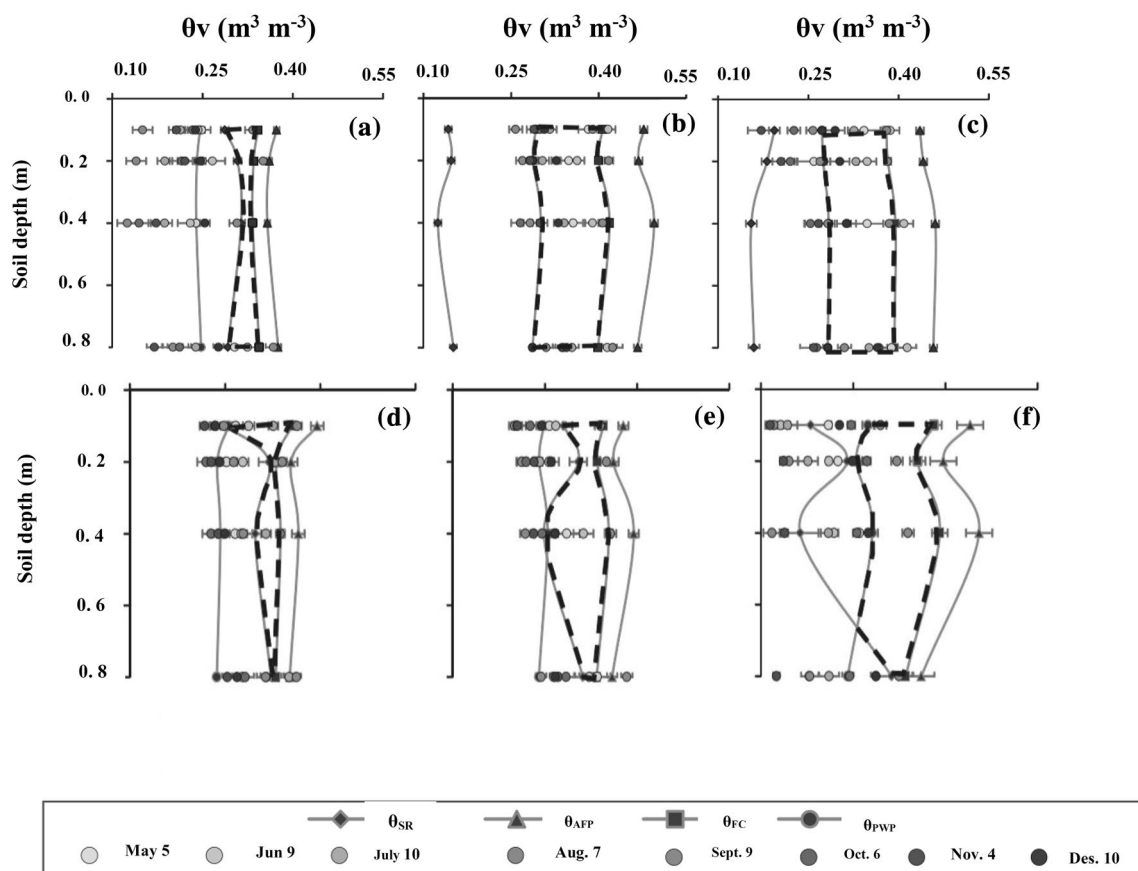
de Souza et al. (2017) investigated the cultivation influence of organic conilon coffee (*Coffea canephora*) intercropped with tree and fruit species on some soil physical attributes including  $D_b$ , SR, and LLWR. The results showed when conilon coffee intercropped with peach palm (*Bactris*



*gasipae*) and *gliciridia* (*gliciridia sepium*),  $D_b$  and SR were lower (1.12 and 1.19 Mg m<sup>-3</sup>, respectively); also, total porosity (0.62 and 0.60 m<sup>3</sup> m<sup>-3</sup>, respectively), micro-porosity (0.49 and 0.46 m<sup>3</sup> m<sup>-3</sup>, respectively), and soil–water content were showed higher (86.33 and 82.85 L m<sup>-3</sup>, respectively) values. Organic coffee shaded with peach palm and *gliciridia* improved the soil physical and hydraulic quality, Compared to the soil under monoculture in full sun, and with the soil of the secondary native forest. The conilon coffee intercropped with peach palm and *gliciridia* demonstrated greater LLWR (almost 0.10 and 0.08 cm<sup>3</sup> cm<sup>-3</sup>, respectively, according to Fig. 1, indicating fewer physical limitations for plant growth in the current condition. Peach palm and *gliciridia* plants, reproduced by cuttings, had a branch root system that led to the creation of an improved structure in the soil with pores attached to the water and gas movement in the soil (de Souza et al. 2015). For treatments that exposed full sun and in system intercropped with banana, LLWR value was the smaller (Fig. 1), due to the soil higher  $D_b$  and lower water retention capacity. For other treatments and

the native forest, SWC was below the lower limit of LLWR ( $\theta_{SR}$  or  $\theta_{PWP}$ ). It shows that in those treatments, soil SR was higher than 2.5 MPa, the critical value of SR for coffee plant that roots could not uptake water from soil beyond that.

Ferreira et al. (2017) studied on the water table management effects on LLWR and potato root growth. The water table surface was managed to target 0.36 and 0.76 m under the soil surface, identified as high (HI) and low (LO) levels, respectively. Undisturbed soil core samples were obtained in the 0–0.15, 0.15–0.30, and 0.30–0.45 m soil layers to determine the LLWR. Root parameters were distinguished using mini-rhizotrons mounted on soil. Overall, LLWR decreased in depth because of a decrease in SOM and an increase in soil  $D_b$ . The LO resulted in a tenuous amplitude for LLWR than HI. In the 0–0.15 m soil layer, the SWC in the HI treatment placed in the LLWR limits with high frequency within the growing season, but both water table surfaces resulted in alike root growth. In opposition, in the 0.15–0.30 and 0.30–0.45 m soil layers, SWC placed in LLWR more often in the LO than HI treatment. The LO management increased



**Fig. 1** Comparison of  $\theta_{AFP}$ ,  $\theta_{FC}$ ,  $\theta_{SR}$ ,  $\theta_{PWP}$  (soil water content at 10% air-filled porosity (AFP), at field water capacity (FC), 2 MPa penetration resistance (SR) and permanent wilting point (PWP), respectively), and least limiting water range (LLWR) for studied soils cultivated with organic conilon coffee (*Coffeacanephora*) in full sun (a),

intercropped with peach palm (*Bactrisgasipae*) (b), *gliciridia* (*gliciridiasepium*) (c), banana (*Musa* sp.) (d), and inga (*Inga edulis*) (e), and in secondary native forest (f) for various dates. Dotted black line indicates the LLWR. Bars represent the standard error

potato root length and surface area in the 0.15–0.30 m soil layer, compared with HI; while in the 0.30–0.45 m soil layer, roots were not present in the HI. Optimum potato root growth was seen when the SWC placed in the LLWR amplitude at the highest frequency during the season.

### Organic carbon

Soil organic carbon (SOC) quantity is an important soil trait that influences many soil properties. Organic binding factors such as roots and fungi perform a serious role in aggregation and soil stability (Tisdall and Oades 1982) and improve soil resistance to environmental tensions (Gregory et al. 2009). Topp et al. (1994) reported a positive relationship between normalized LLWR (LLWR/AWC) and OC. The correlation coefficient between normalized LLWR and OC was 0.41. The results of Verma and Sharma's research (2008) showed that the SR was lower in wheat-soybean-forage crop rotation system, which was the result of adding more OM to soil and, consequently, the soil physical conditions were better than the other crop rotation systems.

Stock and Downes (2008) determined the influence of additions of OM on the SR of a hard-setting soil for the whole water potential amplitude. Their investigation was performed on Saalian glacial till, which was used as the bed of resuscitation in post-lignite-mining reclamation. Proportions used were inclusive of 0, 1, 2, 3, and 4% by mass of OM. Compared to 0% OM, the addition of 1% OM resulted in a significant ( $P < 0.01$ ) increase in the  $D_b$ ; however, the addition of OM between 1 and 4% decreased  $D_b$  linearly. In conditions that SWC was more than FC, SR changes were in consistent with  $D_b$  and its value increased (restrictive for root penetration) for soils with 0–1% organic matter and decreased in treatments with 2–4% organic matter and was not restricting for root penetration.

Chen et al. (2013) concluded that the LLWR value at each depth showed more obviously the differences of soil organic carbon sequestration in the 0–0.05 and 0.05–0.3 m soil depth, compared to the weighted mean of LLWR for whole soil depth, and was more proper for evaluation the situation of soil organic carbon stratification.

### The relation between LLWR and crop production

Productivity is a good index of the soil conditions, since it straightly shows changes in the quality and restrictions of the soil. The major objective of soil management for agriculture is to develop favorite conditions for seed germination, root growth, the emergence of young plants, good crop growth, plant development, grain formation, and harvest (da Silva and Kay 1996).

da Silva and Kay (1996) found a significant correlation between the number of days that water content was out of the

LLWR and corn growth, but study of Benjamin et al. (2003) showed a weak relationship between LLWR and grain yield of maize and wheat, indicating that the effect of other limiting factors was high. In addition, Klein and Camara (2007) found no correlation between it and soybean yield.

### A new definition for upper limit of the LLWR using soil physical properties and physiological characteristics of the plant and prediction of LLWR using plant response

Mohammadi et al. (2010) defined an upper limit of the LLWR ( $\theta_C$ , Eq. 14), on the base of soil physical attributes including  $b$  parameter of the Campbell WRC model, PSD, aeration porosity at 100 cm suction, and physiological properties of the plant (oxygen consumption rate, rooting depth). The UNSODA used soils were as follow: clay, sand, loam sandy clay loam, sandy loam, loamy sand, and silt loam:

$$\theta_C = \theta_s - a_c = \theta_s - a_{100} \left[ \frac{r_g \max L^2}{2C_0 D_0 (2a_{100}^3 + 0.04a_{100})} \right] (1/c + d/b), \quad (14)$$

where  $a_c$  ( $\text{m}^3 \text{m}^{-3}$ ) is the critical aeration porosity below which the symptoms of oxygen deficiency occur,  $a_{100}$  ( $\text{m}^3 \text{m}^{-3}$ ) is the aeration porosity at 100 cm matric head,  $r_g$  is the soil respiration rate ( $\text{mol m}^{-3} \text{s}^{-1}$ ) (Eq. 15);  $L$  is the depth of root zone (m),  $C_0$  is the oxygen concentration of air [ $9.375 \text{ mol m}^{-3}$  (Lide 2002)],  $D_0$  ( $\text{m}^2 \text{s}^{-1}$ ) is the gas diffusion coefficient in air [ $1.38 \times 10^5 \text{ m}^2 \text{s}^{-1}$  (Glinski and Stepniewski 1985)], and  $b$  is Campbell's pore-size distribution index (Campbell 1974):

$$r_g = \left[ \frac{a}{a_{100}} \right]^{(c+d/b)} \times \frac{2C_0 D_0 (2a_{100}^3 + 0.04a_{100})}{L^2}, \quad (15)$$

where  $a$  is the AFP factor,  $c$  and  $d$  are dimensionless empirical fitting parameters of the Moldrup et al. (2000) model (Eq. 16) that is the ratio of the gas diffusion coefficient in soil ( $D_p$ ) to its coefficient in the free air ( $D_0$ ) ( $D_p/D_0$ ):

$$\frac{D_p}{D_0} = (2a_{100}^3 + 0.04a_{100}) (a/a_{100})^{(c+d/b)}. \quad (16)$$

Their results showed that this upper limit depends on the rooting depth, oxygen consumption rate, and  $b$  parameter of the Campbell model (especially in coarse-textured soils with a reduced sensitivity to aeration) (Mohammadi et al. 2010). The sensitivity analysis showed that the upper limit of the LLWR approached the  $\theta_s$  when the consumption rate of oxygen by plants became less than  $2 \mu\text{mol m}^{-3} \text{s}^{-1}$  (Mohammadi et al. 2010). For potato and avocado that are sensitive to aeration restriction, differences between the  $\theta_{UL}$  and the  $\theta_{FC}$  were much (Mohammadi et al. 2010). This result was

true especially for sandy soils (Mohammadi et al. 2010). Results also showed that the soil  $\theta_{AFP} = 10\%$  could not be as an appropriate  $\theta_{UL}$ , because it did not properly reflect the plant water needs (Mohammadi et al. 2010).  $\theta_{UL}$  was more than  $\theta_{FC} = 0.033$  MPa and  $\theta_{FC}$  based on drainage flux rate (Mohammadi et al. 2010). Nachabe (1998) considered when the hydraulic conductivity of soil after initial drainage reaches  $0.05 \text{ mm day}^{-1}$ , the  $h$  value could be considered as the FC point.

Mohammadi et al. (2010) reported that in heavy textured soils, the water content at the upper limit of LLWR was greater than  $\theta_{FC}$ . The maximum rate of oxygen consumption in the soil was usually below  $20 \mu\text{mol m}^{-3} \text{ s}^{-1}$  and increased with increasing water stress, and it was decreased rapidly with increasing  $D_b$  (Mohammadi et al. 2010). A similar trend of the oxygen diffusion rate (ODR) variation with depth and  $D_b$  has been reported by Stepniewski et al. (2005). Also, Wu et al. (2003) observed with increasing soil matric suction, oxygen diffusion ratio of a compacted clay loam and clay soil increased. In soils with heavy texture, there was a significant difference between moisture content at AFP 10%, water content at 330 cm suction, and water content at target suction based on Nachabe (1998) method (Mohammadi et al. 2010).

### Plant response-based LLWR

Kazemi et al. (2018) determined LLWR based on sunflower plant response. Their study evaluated the values of LLWR determined according to the procedures introduced by da Silva et al. (1994) with those calculated on the basis of sunflower plant (*Helianthus annuus L*) response (LLWR<sub>p</sub>). In both methods, LLWR was considered as the difference between the two soil water limits designated as upper ( $\theta_{UL}$ ) and lower limits ( $\theta_{LL}$ ). In the first method, the two limits were determined basically from the soil moisture and soil resistance characteristic curves, almost overlooking the plant type and its particular needs or behaviors. In the second method, the two limits were determined based on the stomatal response in a sandy clay loam soil packed into PVC tubes (called pots) with 30 cm diameter and 70 cm height at three compaction levels (soil  $D_b$  equal to 1.75, 1.55, and  $1.35 \text{ Mg m}^{-3}$ ) designated as  $D_1$ ,  $D_2$ , and  $D_3$ . Each pot was planted with three pre-soaked sunflower seeds and pots were kept under optimum condition until onset of the flowering stage. At that time two successive drying cycles were imposed and soil moisture and midday stomatal conductance were routinely measured. LLWR<sub>p</sub> were computed on the basis of relationship between soil matric suction and stomatal conductance. Results showed that on the basis of stomatal conductance behavior, water uptake began at the soil matric suctions of 44, 16, 60 and continued up to 17,394, 31,614, 39,983 cm in  $D_1$ ,  $D_2$ , and  $D_3$  treatments, respectively.

Appreciable differences were observed between LLWR and LLWR<sub>p</sub>, particularly when the lower limit water potential (equivalent to  $\theta_{UL}$  for LLWR) was set at 330 cm (LLWR<sub>330</sub>). LLWR<sub>330</sub> values of 0.148, 0.147, and  $0.080 \text{ cm}^3 \text{ cm}^{-3}$  were obtained for  $D_1$ ,  $D_2$ ,  $D_3$  treatments, respectively, which were 51, 49, and 63% lower than the corresponding LLWR<sub>p</sub> values. These differences imply that the two moisture limits ( $\theta_{UL}$  and  $\theta_{LL}$ ) proposed by da Silva et al. (1994) may not be applied indiscriminately for all plants and should to be modified according to plant response (Kazemi et al. 2018).

### Integral water capacity (IWC)

Groenevelt et al. (2001) defined IWC as:

$$\text{IWC} = \int_0^{\infty} \left( \prod_{i=1}^n \omega_i \right) C(h) dh, \quad (17)$$

where  $C(h) = - (d\theta/dh)$ , is differential water capacity ( $\text{cm}^{-1}$ ) (the absolute value of  $d\theta/dh$ ),  $\omega_i$  are weighting functions accounting for different restrictive soil properties,  $\Pi$  indicates that the applied weighting functions or coefficients are multiplicative, and  $h$  is the matric potential (positive), expressed in cm. For each limiting factor,  $\omega_i$  varies from 0 to 1. In fact, in IWC concept, it is assumed that the water stored in the soil within 0 to oven dryness is potentially usable by plants, but this potentiality would be practically reduced by various constraint that may be prevailed in root-soil medium (Groenevelt et al. 2001). By introducing the  $\omega_i$  coefficient at the given range of matric potential ( $h$ ), particular limiting factor effect on water uptake is taken into account (Groenevelt et al. 2001). Up to now, the effects of various physical properties including high and lower hydraulic conductivity, aeration limitation, SR (Groenevelt et al. 2001; Asgarzadeh et al. 2010; Grant et al. 2010), and salinity (Groenevelt and Grant 2004; Nang et al. 2010, Meskini-vishkaee et al. 2018) have been considered in the computation of IWC.

According to Eq. 17 to compute the IWC, it is necessary to determine WRC, SRC, and  $K(h)$  of the soil and define weighting functions for various soil limitations. For non-saline soils, at the wet end of WRC, two restrictions might limit water availability for plant including soil high hydraulic conductivity and aeration problem and at dry end of it, higher soil penetration resistance and low hydraulic conductivity (Groenevelt et al. 2001). When soil limitations completely restrict water availability for plants,  $\omega_i(h)$  equals zero, and then with decreasing the limitations, it increases continuously and reaches to unity, when there is no restrictions for water availability by soil properties (Groenevelt et al. 2001).

Groenevelt et al. (2001) and Asgarzadeh et al. (2010) used the van Genuchten (1980) equation (Eq. 18) for computation of IWC. Other appropriate WRC models could be used. Recent researchers fitted van Genuchten (1980) equation to the experimental WRC data:

$$\theta(h) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha h)^n]^{(1-n)/n}, \quad (18)$$

where  $h$  is the soil matric potential and positive (cm),  $\theta(h)$ , soil volumetric water content as a function of  $h$ ,  $\theta_r$  and  $\theta_s$  residual and saturated water contents of soil ( $\text{cm}^3 \text{cm}^{-3}$ ), and  $n$  and  $\alpha$  are fitting parameters with no physical significance.

Groenevelt et al. (2001) also used the van Genuchten (1980)–Mualem (1976) model for the soil hydraulic conductivity ( $K(h)$ ) function (Eq. 19):

$$K_r(h) = [1 - (\alpha h)^{n-1} [1 + (\alpha h)^n]^{-m}]^2 [1 + (\alpha h)^n]^{-m/2}. \quad (19)$$

Here,  $K_r(h)$  is the relative hydraulic conductivity (van Genuchten 1980).

Equation 20 was employed as SRC model (Groenevelt et al. 2001):

$$\text{SR} = ah^b. \quad (20)$$

In Eq. 20, SR is soil penetration resistance (MPa),  $h$  soil matric potential, and  $a$  ( $\text{MPa cm}^{-1}$ ) and  $b$  are empirical fitting parameters (Groenevelt et al. 2001).

Having the weighting functions for various soil limitations, the effective differential water capacity ( $E_i(h)$ ) was calculated using Eq. 21 (Groenevelt et al. 2001):

$$E_i(h) = \omega_i(h) C(h). \quad (21)$$

$C(h)$  ( $\text{cm}^{-1}$ ), is the slope of WRC, and  $\omega_i(h)$  are the weighting functions (a function of soil matric potential) that considers soil different restrictions (1 to  $n$ ) (Groenevelt et al. 2001).

At dry end of WRC and soil water contents near to saturation point, soil water is unavailable for plants due to high drainage velocity and actually  $K(h)$  is limiting factor for water availability (Groenevelt et al. 2001).

Values of weighting function of high soil hydraulic conductivity ( $\omega_k(h)$ ) were calculated by Eq. 22 (Groenevelt et al. 2001):

$$\omega_k(h) = \left( \frac{K_r(330)}{K_r(h)} \right)^P \quad 0 \leq h < 330, \quad h \geq 330 \omega_k(h) = 1, \quad (22)$$

where  $\omega_k(h)$  value was considered equal to unity at  $h$  value of 330 cm and decreased with decreasing soil matric potential (Groenevelt et al. 2001). The corresponding  $E_i(h)$  value for  $K(h)$  ( $E_K(h)$ ) was obtained using Eq. 23 (Groenevelt et al. 2001):

$$E_K(h) = \omega_K(h) C(h). \quad (23)$$

The values for soil aeration weighting function ( $\omega_a(h)$ ) were set to 0 and 1 at soil air filled porosities equal to 10 and 15%, respectively.  $\omega_a(h)$  for intermediate values were acquired using the Eq. 24 (Groenevelt et al. 2001):

$$\omega_a(h) A \log h/h_0 \quad A = 1/\log(h_f/h_0), \quad (24)$$

where  $h_0$  and  $h_f$  are  $h$  values at soil air filled porosities corresponding to 10 and 15%, respectively. For their studied soil, these values of AFP occurred at  $h$  of 60 and 100 cm, respectively. Effective differential water capacity ( $E_{Ka}(h)$ ) when both high soil hydraulic conductivity and aeration problem were limiting was calculated as follows (Groenevelt et al. 2001):

$$E_{Ka}(h) = \omega_K(h) \omega_a(h) C(h). \quad (25)$$

Groenevelt et al. (2001) supposed that soil penetration resistance limitations for plant water availability starts at SR equal to 1.5 MPa ( $\omega_R(h)=1$ ) and completes at 2.5 MPa SR value ( $\omega_R(h)=0$ ). Therefore, they calculated  $\omega_R(h)$  applying Eq. 26 (Groenevelt et al. 2001):

$$\omega_R(h) = 2.5 - (\alpha h)^b. \quad (26)$$

Then,  $E_R(h)$  was obtained by applying the Eq. 27 (Groenevelt et al. 2001):

$$E_R(h) = \omega_R(h) C(h). \quad (27)$$

For the studied soil,  $\omega_R(h)=1$  occurred at  $h$  of 1610 cm; the SR is equal to 2.5 MPa ( $\omega_R(h)=0$ ) at  $h$  of 4198 cm, and with Groenevelt et al. (2001) definition after that  $h$  value, soil water was assumed unavailable for plant.

It was assumed that limitation of low soil hydraulic conductivity ( $\omega_k(h)_{dry}$ ) starts at soil matric potential equal to 12,000 cm and increases with increasing  $h$  and completes at  $h$  value of 15,000 cm. It was obtained by applying Eq. 28 (Groenevelt et al. 2001):

$$\omega_k(h)_{dry} = (12,000/h)^{-b}. \quad (28)$$

Power  $b$  is the appropriate experimental parameter of the function (Groenevelt et al. 2001):

When high values of SR and low values of  $K(h)$  ( $K(h)_{dry}$ ) were limiting for water availability,  $E_{RK}(h)_{dry}$  was calculated by applying Eq. 29 (Groenevelt et al. 2001):

$$E_{RK}(h)_{dry} = \omega_K(h)_{dry} \omega_R(h) C(h). \quad (29)$$

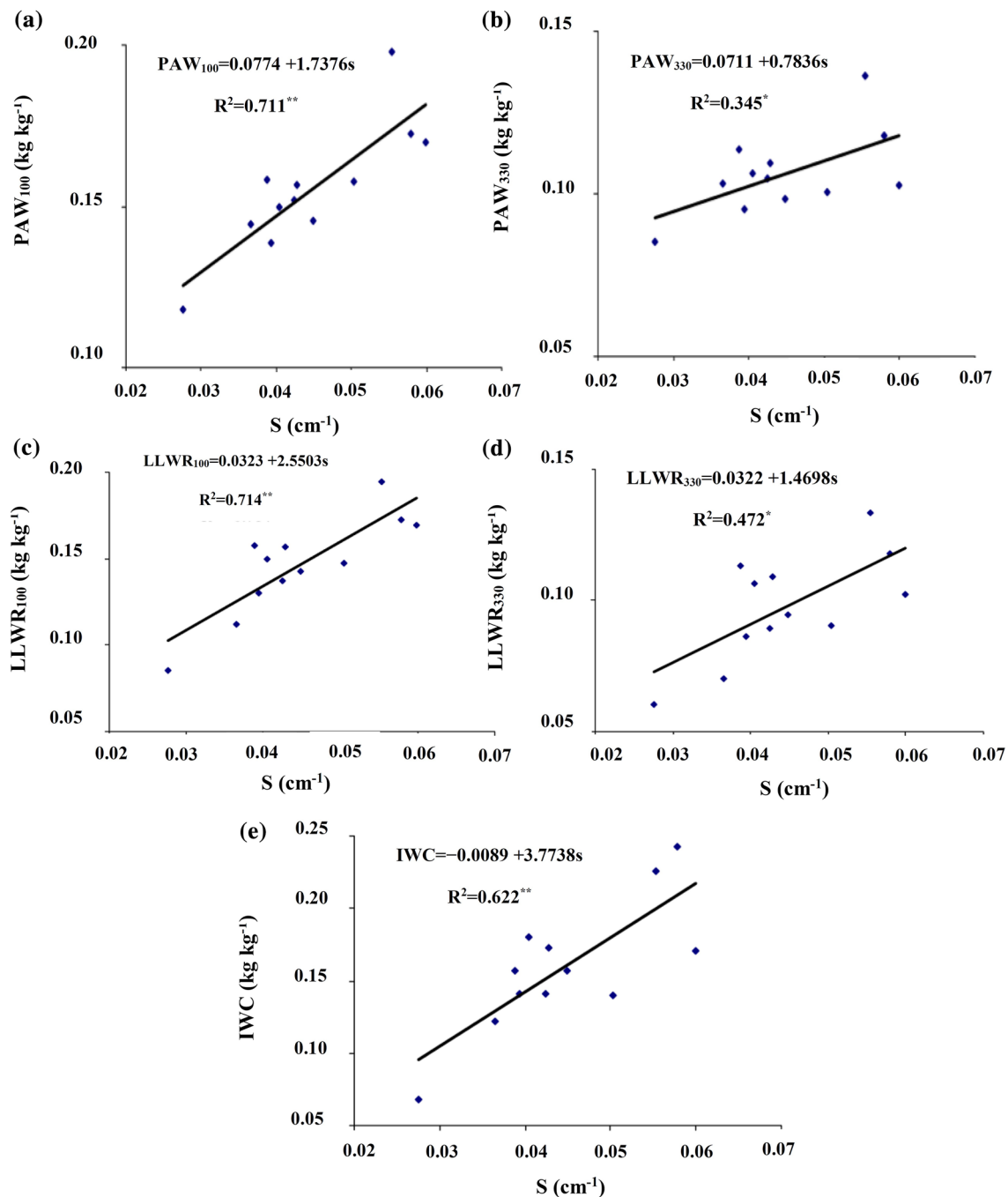
Comparison of IWC value for the non-swelling studied soil with average  $D_b$  of  $1.63 \text{ Mg m}^{-3}$  by Groenevelt et al. (2001) with LLWR showed that their values were not much different ( $0.049, 0.037 \text{ cm}^3 \text{ cm}^{-3}$  compared to  $0.050$ ,



$0.038 \text{ cm}^3 \text{ cm}^{-3}$ , for dry and wet ends of WRC, for IWC and LLWR, respectively).

Asgarzadeh et al. (2010) computed IWC values for 12 soils using Groenevelt et al. (2001) proposed weighting functions and compared with the corresponding values of PAW and LLWR for the studied soils and explored their

correlation with Dexter's  $S$  factor as a soil physical quality index (Fig. 2). They used  $h$  value 100 and 330 cm for the FC. Differences among  $\text{PAW}_{100}$ ,  $\text{PAW}_{330}$ ,  $\text{LLWR}_{100}$ ,  $\text{LLWR}_{330}$ , and IWC were significant ( $P < 0.01$ ). The highest value of them belonged to IWC ( $0.210 \text{ cm}^3 \text{ cm}^{-3}$ ) and the smallest of them were computed for the LLWR ( $0.129 \text{ cm}^3 \text{ cm}^{-3}$ ),



**Fig. 2** The relations between conventional plant available water ( $\text{PAW}_{100, 330}$ ) (a, b), least limiting water range ( $\text{LLWR}_{100, 330}$ ) (c, d), and integral water capacity IWC (e) values and dexters the  $S$  index (Asgarzadeh et al. 2010)

respectively. Except for one soil,  $\theta_{UL}$  of the LLWR for all of the soils was  $\theta_{330}$ .  $\theta_{LL}$  of LLWR for five soils was  $\theta_{PWP}$  and for seven soils,  $\theta_{SR}$ . Due to the selected critical values for soil limitations and gradual changes of soil restrictions versus water content in the IWC computation approach, its value was more than other soil available water concepts computed by Asgarzadeh et al. (2010). The significant relationships obtained between gravimetric PAW, LLWR, and IWC values (Fig. 2) and  $S$  index showed that it was a suitable index to present the soil available water for plants even in the form of IWC (Asgarzadeh et al. 2010). The obtained relationships were positive that indicates the positive influence of soil physical quality and structure on the availability of soil water for plants (Asgarzadeh et al. 2010).

### Plant and soil-based computed IWC

Meskini-Vishkaee et al. (2018) defined new weighting functions for rapid drainage flux ( $\omega_q(h)$ ) and aeration ( $\omega_{ac}(h)$ ) limitations at the wet end and for hydraulic resistance ( $\omega_R(h)$ ), instead of low hydraulic conductivity at dry end of WRC for computing IWC, using soil and plant properties. They named it IWC<sub>p</sub>. Experimental data were gained from a greenhouse study on canola and wheat plants in clay loam and sandy loam soils for 2 years (Meskini-Vishkaee et al. 2018).

### The new weighting functions for wet end of WRC

**Rapid drainage** Meskini-Vishkaee et al. (2018) defined the following weighting function (Eq. 30) for rapid drainage flux:

$$\omega_q(h) = \left( q_{FC} / q_h \right) = \exp \left[ K_s / Q_\infty (t - t_{FC}) \right], \quad (30)$$

where  $q_{FC}$  ( $ms^{-1}$ ) is the drainage flux rate at  $h_{FC}$ ;  $q_h$  ( $ms^{-1}$ ) is drainage flux rate at each soil matric potential ( $h$ ), where  $h_e < h < h_{FC}$ .  $h_e$  (m) is the soil  $h$  at the air entry value.  $K_s$  ( $m s^{-1}$ ) is the saturated hydraulic conductivity,  $Q_\infty$  (m) is the total drainable water to soil depth  $z$  (m) after infinite time,  $Q_\infty = z(\theta_s - \theta_r)$ , and  $t_{FC}$  (s) is the time to reach to the FC. When  $t > t_{FC}$  the left side of Eq. 30 equals to 1. Using  $\omega_q(h)$ , the  $E_q(h)$  ( $m^{-1}$ ) was calculated as (Meskini-Vishkaee et al. 2018):

$$E_q(h) = \omega_q(h)C(h). \quad (31)$$

Assouline and Or (2014) model who suggested  $h_{FC}$ , instead of  $h$  100 or 330 cm for FC is as:

$$h_{FC} = 1/a * \left( n - 1/n \right)^{(1 - 2n)/n}, \quad (32)$$

where  $a$  ( $m^{-1}$ ) and  $n$  are fitting parameters of van Genuchten (1980) model.

$t_{FC}$  could be obtained by:

$$t_{FC} = -\frac{Q_\infty}{K_s} \ln \left( \frac{K(S_{FC})}{K_s} \right), \quad (33)$$

where  $K(S_{FC})$  is the soil hydraulic conductivity as a function of  $K(S_{FC})$  and could be calculated using Eq. 34 and  $S_{FC}$  by Eq. 35 (Meskini-Vishkaee et al. 2018):

$$K(S_{FC}) = K_s S_{FC}^{0.5} \left[ 1 - \left( S_{FC}^{\frac{1}{m}} \right)^m \right]^2 \quad (34)$$

$$S_{FC} = S(h_{FC}) = \left( \frac{\theta_{FC} - \theta_r}{\theta_s - \theta_r} \right) = \left\{ 1 + (a|h_{FC}|^n)^{\left( \frac{1-n}{n} \right)} \right\}, \quad (35)$$

where  $m = 1 - 1/n$  and  $K_s$  ( $m s^{-1}$ ) is the saturated hydraulic conductivity. Other parameters have been introduced, previously.

**Aeration limitation** Meskini-Vishkaee et al. (2018) also defined a new weighting function for aeration limitation ( $\omega_{ac}(h)$ ) at the wet end of WRC (Eq. 36). The current researchers assumed that restriction rate due to oxygen deficit was proportional to the soil respiration rate:

$$\omega_{ac}(h) = \frac{r_g}{r_g \max} = \left( \frac{a}{a_c} \right)^{c+d/b}. \quad (36)$$

$\omega_{ac} = 0$ , where  $h \leq h_e$  or  $a = 0$   
and

$\omega_{ac} = 1$ , where  $h = h_{ac}$ .

Where  $a$  ( $m^3 m^{-3}$ ) is aeration porosity at each  $h$ , (m), when  $h_{ac} < h < h_e$ .  $h_{ac}$  is the soil matric potential at the critical aeration porosity ( $a_c$ ).  $h_{ac}$  (m), was calculated from  $\theta_c$  ( $m^3 m^{-3}$ ) (Eq. 14), using the van Genuchten (1980) model for WRC as follows (Meskini-Vishkaee et al. 2018):

$$h_{ac} = \frac{\left( \left( \frac{\theta_c - \theta_r}{\theta_s - \theta_r} \right)^{\frac{n-1}{n^2}} - 1 \right)}{a}. \quad (37)$$

The parameters of recent equation have been introduced previously in Eqs. 14 and 18

### The new weighting functions for high hydraulic resistance of soil ( $R_s$ ) at dry end of WRC

Meskini-Vishkaee et al. (2018) also defined a new weighting function as a function of soil and plant properties  $\omega_R(h)$  (Eq. 38) at the dry end of WRC for soil hydraulic resistance ( $R_s(h)$ ) (m s):

$$\omega_R h \frac{R_{hc}}{R_h} \quad \text{for } h > h_c; \quad \omega_R(h) = 1 \quad \text{for } h \leq h_c, \quad (38)$$

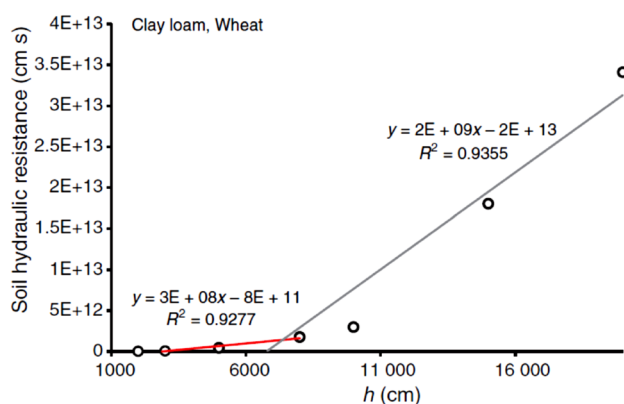
where  $R_{hc}$  is the critical value of  $R(h)$ ;  $Rh$  (m s) is the soil hydraulic resistance corresponding to each  $h$  value in the soil that is more than  $h_c$ .

Meskini-Vishkaee et al. (2018) used Eq. 39, expressed by Gardner (1960) for defining the new weighting function:

$$R_s = \frac{\ln(r^2 RLD \pi)}{4\pi \cdot K(h) RLD}, \quad (39)$$

where  $r$  (m) is root radius,  $RLD$  ( $\text{mm}^{-3}$ ) root length density, and  $K(h)$  the soil hydraulic conductivity. According to Eq. 39, there is an adverse relation between  $R(h)$  with  $K(h)$  and  $RLD$ . In a drying soil,  $R(h)$  increases with decreasing  $K(h)$  and the contact surface between roots and the soil water (Miyazaki 2005).

Meskini-Vishkaee et al. (2018) determined  $R_{hc}$  by plotting the  $R_s$ - $h$  curve (For plant wheat in clay loam soil it has depicted by Fig. 3). They considered  $R_{hc}$ , where a sharp rise in  $R_s$ - $h$  curve occurred and the corresponding  $h$  considered as  $h_c$  (m) (Fig. 3). Indeed, the soil hydraulic resistance limitation for water uptake by plants starts from  $h_c$ . Meskini-Vishkaee et al. (2018) followed the Oosterbaan et al. (1990) method to fit two separate regression lines to the dataset for acquiring the least-squares. Each regression line was taken to represent one segment of the  $R_s$ - $h$  curve and the crossing



**Fig. 3** Soil hydraulic resistance ( $R_s$ ) values as a function of soil matric potential ( $h$ ) for wheat plant in the clay loam soil (Meskini-Vishkaee et al. 2018)

points of the two lines were assumed as the breakpoint (Oosterbaan et al. 1990).

Meskini-Vishkaee et al. (2018) computed  $IWC_p$  for wheat and for wheat using the above plant and soil-based weighting functions and compared them with LLWR. The  $IWC_p$  values obtained for wheat were  $0.205$  and  $0.202 \text{ m}^3 \text{ m}^{-3}$  and  $0.194$  and  $0.189 \text{ m}^3 \text{ m}^{-3}$  for canola in clay loam and sandy loam and soils, respectively (Meskini-Vishkaee et al. 2018). The values of  $LLWR_{100}$  and  $LLWR_{330}$ , for sandy loam soil were  $0.138$  and  $0.072 \text{ cm}^3 \text{ cm}^{-3}$ , respectively, and for clay loam soil  $0.156$  and  $0.092 \text{ cm}^3 \text{ cm}^{-3}$ , respectively, versus the  $IWC_p$  values obtained for wheat and canola in those soils. The differences in the  $IWC_p$  between canola and wheat in the same soils indicated the necessity of interfering plant attributes in addition to soil condition to obtain real PAW in the form of IWC. These differences would be even more appreciable for root systems with a wider range of different properties (Meskini-Vishkaee et al. 2018).

Neyshabouri et al. (2018) computed IWC in a sandy clay loam soil using midday green leaf temperature ( $T_L$ ) of sunflower plant (*Helianthus annuus* L.) at different soil compaction levels ( $D_b$  equal to  $1.35$ ,  $1.55$ , and  $1.75 \text{ Mg m}^{-3}$ , respectively,  $D_1$ ,  $D_2$ , and  $D_3$  treatments) in a greenhouse trial. After determining daily SWC at soil and converting them to soil matric potential along with the midday  $T_L$  measurements, Neyshabouri et al. (2018) created a weighting function on the base of plant response and computed IWC ( $IWC_p$ ) using it. Furthermore, IWC was computed by applying weighting functions developed by Groenevelt et al.'s (2001) procedure ( $IWC_G$ ). The value of  $IWC_p$  for  $D_1$  treatment was  $0.187 \text{ cm}^3 \text{ cm}^{-3}$  in comparison to  $0.229 \text{ cm}^3 \text{ cm}^{-3}$  for  $IWC_G$ . For  $D_3$  treatments with  $D_b$  of  $1.75 \text{ Mg m}^{-3}$ , the corresponding values diminished to  $0.152$  and  $0.038 \text{ cm}^3 \text{ cm}^{-3}$ , respectively (equivalent to 19 and 84% reduction in IWC) indicating the dominant influence of soil  $D_b$  on water availability. The mean values of  $IWC_p$  and  $IWC_G$  for  $D_1$ ,  $D_2$ , and  $D_3$  treatments were  $0.169$  and  $0.14 \text{ cm}^3 \text{ cm}^{-3}$ , which shows that  $IWC_p$  was 17% greater than  $IWC_G$ . The results indicate that the weighting functions introduced by Groenevelt et al. (2001) for various soil limitations must be modified in the base of plant response to various restrictions.

Kazemi et al. (2019) also evaluated the effect of root length density on IWC in sunflower (*Helianthus annuus* L.) plant in Neyshabouri et al. (2018) studied soil and plants. After full establishment of sunflower seedlings at the end of vegetative growth and onset of reproductive growth, four levels of RLD was created by pruning root branches (approximately 75, 50, 25, and 0% that was named  $L_1$ - $L_4$ , respectively) around the root crown. Two periods of wetting and drying cycles were imposed. IWC was computed first by adopting and introducing RLD in the form of soil hydraulic resistance ( $IWC_{RS}$ ) and compared with  $IWC_G$ . The results showed differences between  $IWC_{RS}$  for the  $D_b$  treatments

and for the L levels were significant. Contrary to  $IWC_G$ , for  $IWC_{RS}$ , the  $h$  value in which water availability restriction for the plants started was different for each soil compaction and each root pruning level. Comparing the means among  $IWC_G$  and  $IWC_{RS}$  at different D and L levels showed significant differences between  $D_1$  treatments and  $L_1$  and  $L_2$  levels.

Khalifezadeh et al. (2019) conducted a study on the critical amount of soil physical quality indexes based on wheat growth properties. In their experiment, it was found that IWC amounts of  $0.136$  and  $0.104 \text{ cm}^3 \text{ cm}^{-3}$  were for the start and endpoint limitations, respectively. IWC values more than  $0.136 \text{ cm}^3 \text{ cm}^{-3}$  demonstrated good soil physical conditions for wheat growth (Khalifezadeh et al. 2019). Low physical limitations were observed for wheat growth in the IWC range of  $0.136$  and  $0.104 \text{ cm}^3 \text{ cm}^{-3}$ .

Chahal (2010) identified the critical  $h$  value ( $h_c$ ) (before that there was no restriction for water uptake by plants,  $(\omega_i(h) = 1)$ , and the  $h$  value where measuring of  $g_s$  was impossible after that ( $h_w$ ),  $(\omega_i(h) = 0)$ , using the daily measured relative stomatal conductance ( $g/g_c$ ) values (Eq. 40) for sorghum and maize in very fine sand and sandy loam texture soils.  $g$  and  $g_s$  indicate the stomatal conductance values at under stress and control treatments, respectively. The only restriction of those soils was lower hydraulic conductivity. The study was for different planting densities (1, 3, and 5 plant in each 3.3 L volume pot) and different evaporative demands [high demand (HET) and low demand (LET)]:

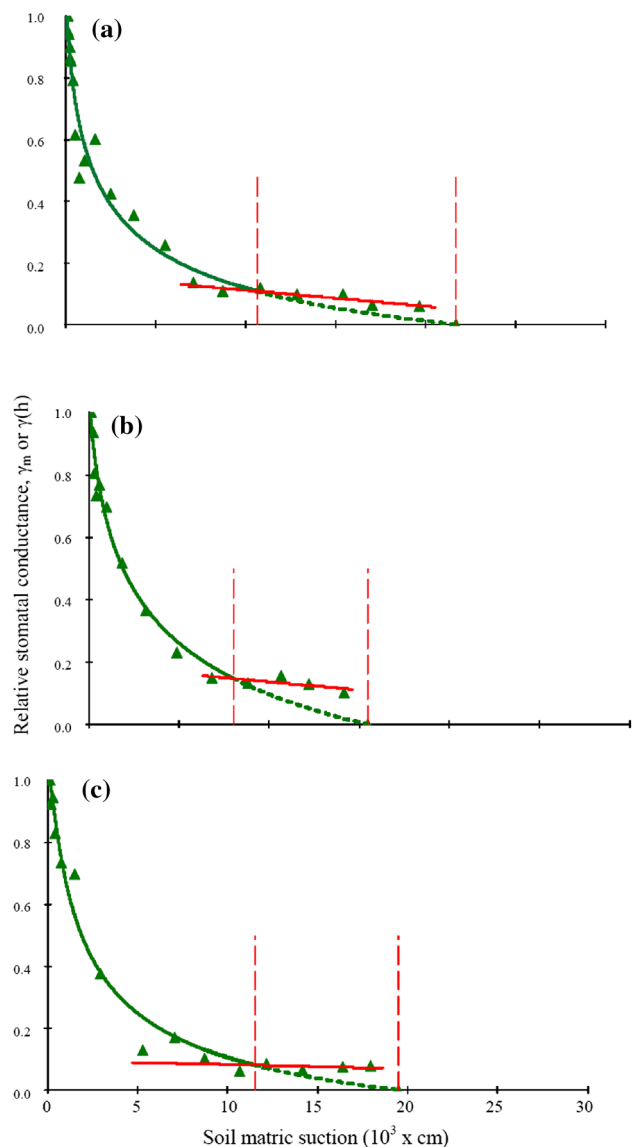
$$\frac{g}{g_c}(h) = \gamma(h) = 1 - \exp \left[ \left( \frac{\beta}{h_w} \right)^\eta - \left( \frac{\beta}{h} \right)^\eta \right], \quad (40)$$

where  $\beta$  units of  $h$  that was cm in Chahal (2010) study) and  $\eta$  dimensionless) are the fitting parameters. The measured and predicted relative stomatal conductance ( $g/g_c$ ) values as a function of  $h$ , for Sorghum plant in loamy sand soil and under LET condition for 1, 3, and 5 plant per pot (a, b and c, respectively) are depicted by Fig. 4.

Chahal (2010) defined a new weighting function using the  $h_c$ ,  $h_w$  and the fraction of fresh mass for pots with 5 plants to the mass for pots containing 1, 3, and 5 plants per pot ( $\rho$ ):

$$\omega(h) = \left( \frac{1 - \left( \frac{h}{h_w} \right)^2}{1 - \left( \frac{h_c}{h_w} \right)^2} \right)^\rho. \quad (41)$$

$h_t$  value was different dependent to soil texture class, plant species, evaporative demand, and plant density (Table 2). In loamy sand soil,  $h_w$  was more than 15,000 cm classic  $h$  value for sorghum, HET, and LET and all plant densities (Table 2). For maize plant in LET condition, its value was 17,159 just for 5 plants per pot in the same soil. For other treatments and especially for very fine sand, its value was



**Fig. 4** Relative stomatal conductance ( $g/g_c$ ) values as a function of soil matric potential ( $h$ ), its predicted (green line) and measured (triangles) values for Sorghum in loamy sand soil and under LET condition for 1, 3, and 5 plants per pot (a–c, respectively) using Eq. 40. The red line was predicted using  $\gamma(h) = g/g_c(h) = a + bh$  ( $a$  and  $b$  are the intercept and slope of the red line, respectively). Vertical dashed lines show the  $h$  values at the start and end of the terminal phase, where  $\omega(h)$  value started to close to 0 (Chahal 2010)

very lower than 15,000 cm (Table 2). The effect of planting density was not considerable due to the lack of variation in their value (0.6 and 1). Furthermore, the evaporative demand had a little effect on total water extracted by plants and the only difference was in the time for plants to extract the water (less time was required for plants to extract water from the HET pots than the LET). It was different dependent to soil



**Table 2** The soil matric potential values for  $h_t$  ( $\omega_t(h)=1$ ) and  $h_w$  ( $\omega_t(h)=0$ ) for Mays and Sorghum plants in loamy sand and very fine sand soil textures, under two evapo-transpirative demand conditions (LET and HET) for different plant densities (1, 3, 5 plants per pot) (Chahal 2010)

Evapo-transpirative demand	Plant density	Soil matric potential ( $h$ ) (bar)				IWC	
		Sorghum		Mays		Sorghum	Mays
		$h_t$	$h_w$	$h_t$	$h_w$		
Loamy sand soil (fine texture class)							
LET	1	10.6	21.7	3.9	12.4	0.199	0.196
	3	8	15.4	2.3	10.3	0.198	0.195
	5	11.5	19.5	6	17.2	0.199	0.198
HET	1	5.2	26.4	3.9	12.2	0.199	0.196
	3	6.5	24	6.9	22.7	0.199	0.199
	5	5.3	20.6	6.2	24	0.199	0.199
Very fine sand (coarse texture class)							
LET	1	0.93	2.7	1.9	3.6	0.129	0.133
	3	1.2	2.8	1.8	4.6	0.130	0.134
	5	1.7	3.4	0.91	2	0.132	0.1236
HET	1	1.4	6.6	0.84	6.9	0.135	0.135
	3	1.5	3.8	0.85	5.7	0.132	0.134
	5	1.6	4.4	0.72	3.1	0.133	0.131

texture class, plant species, evaporative demand, and plant density (Table 2).

The predicted IWC value for loamy sand soil was closed to the water values that were computed using the daily extracted water (Chahal 2010). The IWC value for loamy sand soil for sorghum at all three densities was equal to 0.199 for both LET and HET conditions. For corn plant in planting densities of 1, 3, and 5 plants per pot under LET conditions, and its value was 0.196, 0.195, and 0.198  $\text{cm}^3 \text{cm}^{-3}$ , respectively. For the HET conditions, the corresponding values were 0.196, 0.199, and 0.199  $\text{cm}^3 \text{cm}^{-3}$  (Table 2).

## Soil salinity

Groenevelt et al. (2001) did not consider the effect of salinity on IWC concept. Whereas, with semipermeable plant cell membranes (root cell membrane with membrane reflectance coefficient,  $\bar{O}$ ), the osmotic potential of the soil solution affects water uptake (Groenevelt and Grant 2004). The value of  $\bar{O}$  varies between 0 and 1, depending on the membrane properties and the species of soluble salts [for most plants, it is greater than 0.8 (Nobel 1974)]. Under these conditions, the maximum PAW is obtained (Groenevelt and Grant 2004). Indeed, as salinity increases, osmotic flow decreases from surface of root into root and, consequently, PAW decreases (Groenevelt and Grant 2004).

Groenevelt and Grant (2004) involved the salinity factor in IWC in the form of soil electrical conductivity (EC). In their view, the sum of the osmotic and matric potentials causes soil water availability changes for plant, so, when sum of these two potentials reach  $-1.5$  MPa, water absorption

stops. Of course, vascular plants can partially sustain water uptake using several mechanisms to maintain the water potential difference between the plant (root) and the soil, especially by osmotic adjustment, reducing the potential for root water to soil, so water absorption continues (Zimmermann et al. 2002; Hillel 1980).

Groenevelt and Grant (2004) studied the amount of available water in the form of IWC for 5 values of osmotic pressure at saturation ( $h_{os}$ ) and electrical conductivity of saturated extract ( $EC_s$ ) in a loamy sand soil and created a weighting function for salinity as follows (Groenevelt and Grant 2004):

$$\omega_{o\min}(h_m, h_{os}) = [1 + h_{os}\theta_s\theta^{-2}C(h_m)]^{-1} \quad 1 \text{ cm} < h_m < 15,000 \text{ cm}, \quad (42)$$

where  $h_m$ ,  $h_{os}$ ,  $\theta$ , and  $\theta_s$  represent matrix pressure, osmotic pressure in saturated mulch extract, SWC in  $h_m$  suction, and saturation,  $\omega_{o\min}$ , weighting coefficient for salinity (assuming  $\bar{O}=1$ ), respectively. Groenevelt and Grant (2004) by interfering salinity with the above weighting function showed that the IWC content in the soil tested at two salinity levels of 1.11 and 2.22  $\text{dS m}^{-1}$  saturated extract, dropped by 55 and 68%, respectively, compared to the IWC values that soil salinity was ignored.

The above computations have been done by assuming  $\bar{O}=1$  and ignoring all other inhibitory properties.

Grant et al. (2010) evaluated PAW during the restoration of saline soils using the IWC concept. The value of IWC in the lack of all physical limitations except high salinity was measured for a saline soil profile. Results showed that when osmotic stresses were considered, the

IWC was about 33% less than that computed when salinity restriction was not taken into account (Grant et al. 2010).

Mohammadi and Khataar (2017) created a new weighting function for soil salinity and estimation of water availability in saline soils using evapotranspiration rate, plant salt tolerance, irrigation water salinity, soil hydraulic attributes, and two clay and sandy loam soils gained from the UNSODA hydraulic properties database (Nemes et al. 2000). The studied plants were corn (sensitive to salinity), cowpea (moderately resistance), and barley (resistant) (Tanji and Kielen 2002). Evapotranspiration rates were as 0.5 and 1 cm d<sup>-1</sup>. Three levels of salinity of the irrigation water (EC<sub>0</sub>): 1.5, 4, and 8 dS m<sup>-1</sup> for corn; 4, 7, and 11 dS m<sup>-1</sup> for cowpea; and 4, 13, and 20 dS m<sup>-1</sup> for barley. The boundaries and weighting functions of the IWC concept proposed by Groenevelt et al. (2001), and augmented by Groenevelt and Grant (2004) for saline soils, have been chosen somewhat arbitrarily (Mohammadi and Khataar 2017). Their new weighting function for salinity was as follows:

$$\omega_{si} = 1 \quad 0 < EC_i \leq EC_T \quad (43)$$

$$\omega_{si} = 1 - \frac{EC_i - EC_T}{EC_F - EC_T} \quad EC_T < EC_i < EC_F \quad (44)$$

$$\omega_{si} = 0 \quad EC_i \geq EC_F, \quad (45)$$

where EC<sub>i</sub> is electrical conductivity of irrigation water and could be calculated by Eq. 45:

$$EC_{i+1} = \left( \frac{\theta_i - \frac{D_{i+1}-D_i}{zL}}{\theta_{i+1} + \frac{D_{i+1}-D_i}{zL}} \right) EC_i, \quad (46)$$

where  $L$  is soil depth (m),  $D$  is downward drainage water depth (m),  $\theta_i$ ,  $D_i$ ,  $EC_i$ , and  $ET_i$  denote the approximate value of  $\theta$ ,  $D$ ,  $EC$ , and  $ET$  at the  $i$ th discrete time level ( $t_i$ ), respectively. Subsequently,  $D_{i+1}$  and  $EC_{i+1}$  denote drainage and evapotranspiration at the time level  $t_i + \Delta t$ , respectively (Mohammadi and Khataar 2017):

$$D_1 = D_\infty \left[ 1 - \exp \left( -\frac{K_m}{D_\infty} t_i \right) \right], \quad (47)$$

where  $D_\infty$  is total drainage water depth (m), defined as  $D_\infty = L(\theta_s - \theta_r)$ ;  $\theta_r$  is residual volumetric SWC (m<sup>3</sup> m<sup>-3</sup>);  $\theta_s$  is saturated volumetric SWC (m<sup>3</sup> m<sup>-3</sup>); and  $K_m$  is weighted mean soil hydraulic conductivity (m s<sup>-1</sup>) and can be estimated using the soil hydraulic conductivity curve (Mohammadi and Khataar 2017).

EC<sub>T</sub> (threshold electrical conductivity) and EC<sub>F</sub> (soil electrical conductivity beyond which the yield is zero) were assumed to be plant specific given in the literature

(e.g., Tanji and Kielen 2002). Their approach allows the prediction of critical and lower limits of the SWC available for plants. Since Mohammadi and Khataar (2017) model is based on the plant parameters, it could be used for modeling the hydrological process of terrestrial ecosystems at large scales. It also could be useful in evaluating the temporal variation of water content and salinity in saline soils. They have analyzed the sensitivity of model results to underlying parameters using characteristics given for barley, corn, and cowpea in the literature and two sandy loam and clay soils gained from the UNSODA hydraulic properties database (Nemes et al. 2000). Results of sensitivity analysis for model results showed that both critical and lower limits (in terms of water content) of soil water uptake by plants increased with evapotranspiration rate and irrigation water salinity (Mohammadi and Khataar 2017).

Mohammadi and Khataar (2017) reported that for a given soil and  $ET$ ,  $h_c$  (the critical value of  $h$  which water can be taken up by a plant without any limitation by salinity = the upper limit of water availability for plant) decreased inconsistent with the sensitivity of the plant to salinity. In the clay soil with  $ET$  equal to 0.5 cm d<sup>-1</sup> and  $EC_0 = 4$  dS m<sup>-1</sup>,  $h_c$  for cowpea and corn was 10,825 and 0 cm, respectively. The values of  $h_c$  for two soils in a given  $EC_0$ ,  $ET$ , and plant type showed the effect of soil hydraulic properties on the plant water uptake under salinity stress. For example, for corn plant at  $EC_0$  equal to 1.5 dS m<sup>-1</sup> for sandy loam and clay soil,  $h_c$  value was 980 and 3565 cm, respectively. Also, the value of  $h_c$  depended on the meteorological conditions. At  $ET$  values equal to 1 cm day<sup>-1</sup>, soil hydraulic conditions limited water uptake at lower  $h$  values (Mohammadi and Khataar 2017). The current researchers also determined the lower limit of water availability for plant ( $\theta_l$ ) using the weighting function proposed for soil salinity. The results showed for  $ET$  equal to 1 cm d<sup>-1</sup> and  $EC_0 = 4$  dS m<sup>-1</sup>,  $h_l$  for barley, cowpea, and corn were 0.016, 0.020, and 0.025 m<sup>3</sup> m<sup>-3</sup>, respectively. The corresponding  $h$  values for them were out of the range of the soil water characteristics curve. The value of  $\theta_l$  also depended on the atmospheric demand conditions. Under high evaporative demand conditions,  $\theta_l$  had high value. For cowpea in clay soil for  $ET = 1$  cm day<sup>-1</sup> and  $EC_0$  equal to 11 dS m<sup>-1</sup>, PWP occurred at  $h$  value of 3200 cm, indicating that in saline soils, applying  $h$  of 15,000 cm as PWP resulted in overestimation of real value of soil available water, especially for sensitive crops and under high evaporative demand conditions (Mohammadi and Khataar 2017).

Farahania et al. (2020) studied the effect of the ratio of potassium to nitrogen (K/Na) on PAW, LLWR, and IWC, and reported that PAW and IWC were increased with increasing this ratio. It is noteworthy that in their study, LLWR was equal PAW. The decrease in soil pore size due to the dispersion of clay particles could be a possible reason

of increasing these parameters. In the treated soils, PAW and IWC at two EC levels (3 and 6  $\text{dSm}^{-1}$ ) were higher than the control. Compared to the control treatment, at these EC levels, PAW increased 54 and 39% and IWC 36 and 24%, respectively.

## Conclusions

Up to now, the influence of various soil attributes on the recent concept of soil available water (IWC) have not studied using plant response in the field. Furthermore, root length density (RLD), which has an important rule on water uptake by plants (Besharat et al. 2010; Blum 2011; Vadez et al. 2007), and its effect on IWC has not been studied. Contrary to Groenevelt et al. (2001), Grant et al. (2010), and Asgarzadeh et al. (2010), water flow from the bulk soil towards the root surface and thus water absorption is not only dependent on the soil  $K(h)$ , but RLD as well. Several researchers have described the combined effects of hydraulic conductivity and root length density in the form of soil hydraulic resistance (Acevedo Hinojosa 1975; Hasegawa 1981; Hasegawa and Sato 1985; Meskini-Vishkaee et al. 2018), implying the necessity of incorporating RLD in determining of IWC. Appropriate weighting functions should be defined using plant indices and considering RLD for various plants and soil textures in the field condition to compute the IWC.

## Future perspectives

We hope that, in the next studies, the researchers consider plant physiological characteristics like transpiration and photosynthesis rate, chlorophyll index, LWP, RWC,  $g_s$ , and canopy or leaf temperature and plant morphological characteristics beside interfering root length density effect, instead of using only soil properties for computing plant real available water in the field or greenhouse and providing more attractive results.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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