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Influence of soil type on the wilting of plants

E.A. Czyż[1,2] *and A.R. Dexter*[1]

[1]Institute of Soil Science and Plant Cultivation (IUNG-PIB), Czartoryskich 8, 24-100 Puławy, Poland
[2]Faculty of Biology and Agriculture, Rzeszów University, Aleja Rejtana 16c, 35-959 Rzeszów, Poland

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Abstract. It has been shown that the water remaining in soil when plants wilt due to soil limitations and the residual water content as observed when soils are de-watered in pressure cell apparatus are essentially the same. Both are produced by immiscible displacement of water by air, and this leads to the water remaining in soil not being in thermodynamic equilibrium. Water removal by immiscible displacement ceases when hydraulic cut-off is reached. The point of hydraulic cut-off may be calculated by fitting water-retention data to equations for both the non-equilibrium case and the equilibrium case, and then solving these simultaneously. This has been done for water retention data for 52 soil horizons in Poland. These results are used to obtain a pedotransfer function for the permanent wilting point due to soil limitations and the results are presented for the different soil texture classes. The pore water suction when wilting occurs is estimated to be 1.0 MPa. The methods and findings in this paper are used to explain a range of published results on plant wilting.

Keywords: hydraulic cut-off, pedotransfer function, permanent wilting point, residual water content, water retention

INTRODUCTION

The de-watering of moist soil by transpiring plants and the de-watering of soil samples in a pressure plate apparatus both occur by the physical process of convective movement of water in the soil by immiscible displacement *ie* air displaces the water (Czyż and Dexter, 2012). This explains why the water remaining in soil when plants of many species wilt is very close to the amount of water remaining in soil samples when they are de-watered in a ceramic pressure plate extractor with an applied air pressure of $P_a = 1.5$ MPa (Richards and Weaver, 1943). This convective movement is completely different from the movement of water by diffusion. Whereas diffusion leads to water in thermodynamic equilibrium, immiscible displacement can lead to systems not in thermodynamic equilibrium. When a system is in thermodynamic equilibrium, all the water has the same specific free energy. In contrast, when it is not in thermodynamic equilibrium, different 'packets' of water within the soil can have different values of specific free energy: for example, they can have different values of pore water pressure or suction. Dexter *et al*. (2012) concluded that for every drying soil, two different water retention curves are needed: one for cases where de-watering occurs by immiscible displacement and one for cases where de-watering occurs by diffusion. Another curve is needed for soil wetting because of the hysteresis effect, but this case is not considered here.

A water retention curve for a soil shows how the water content decreases with increasing pore water suction. The subject of water retention curves was discussed in detail by Fredlund and Xing (1994), however those authors did not distinguish between the above two physical processes of de-watering. Here, we follow Dexter *et al*. (2012) by using the Dexter *et al*. (2008) double-exponential (DE) water retention equation for immiscible displacement and the Groenevelt and Grant (2004) water retention equation (GG) for cases where equilibrium has been attained by diffusion.

The Dexter *et al*. (2008) equation is based on the concept of a bi-modal pore size distribution as described by Monnier *et al*. (1973) and Stengel (1979). In this model, the pore space is divided into two parts: the textural porosity which occurs between the primary mineral particles; and the structural porosity which occurs between micro-aggregates and/or any other compound particles. With increasing pore water suction, the largest pores *ie* the structural pores empty first. Then, at larger values of suction the smallest pores *ie* the textural pores empty. Any water which remains is the residual water which is either adsorbed water or water that cannot drain because it is not connected to the outside of the sample through continuous, water-filled pore space.

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*Corresponding author e-mail: ewac@iung.pulawy.pl

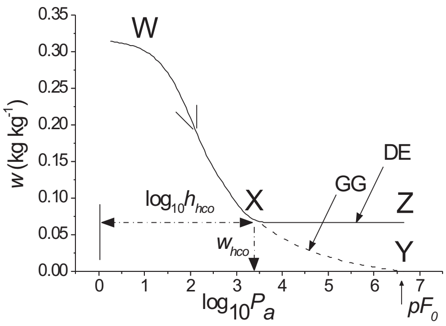

Fig. 1. Examples of water retention curves presented to define some of the terms used. A plot of the Groenevelt and Grant (GG) equation covers the portions of the curve WX and XY, and represents soil water in thermodynamic equilibrium. The water content, w, goes to zero at point Y (pF_0). With immiscible displacement, as described by the double-exponential (*DE*) equation, dewatering occurs only in the curve portion WX. Other features are described in the text.

Figure 1 shows examples of these two curves for a hypothetical soil. In order to facilitate the discussion, we have divided the curves into three sections defined by the points shown as W, X, Y and Z in Fig. 1. When the mechanism of de-watering is diffusion, then the curve followed is WXY. The water content becomes zero at a finite value of free energy. Detailed measurements on seven French soils, showed that the water content would become zero at a value pore water suction of 450 M Pa or pF_0 = 6.653. Use of the Kelvin equation showed that this is equivalent to a value of relative humidity = 3.6% at 20°C (Dexter and Richard, 2009; Kutilek and Nielsen, 1994). We use the same value here.

When the mechanism of de-watering is immiscible displacement, then de-watering ceases at point X, and further increase in applied pressure, P_a, has no effect on the water content which remains constant over the curve section XZ at a value of $w = w_{hco}$. Point X is called the hydraulic cut-off point. The water content, w_{hco}, at this point is equal to both the residual water content, *C*, and that at the permanent wilting point, *PWP*, for cases where water extraction by plants is soil-limited.

MATERIALS AND METHODS

Soil samples were collected from 52 soil horizons from a range of sites in Poland. About one-half of the sites were on fields belonging to agricultural experiment stations and about one-half were on private, commercial farms. All the samples were from the upper 60 cm of the soil. Samples were collected in 100 ml stainless steel cylinders, were sealed in double plastic bags to prevent water loss, and were stored in a cool room until they were required. Twenty-six cylinders of soil were collected from each soil horizon: 22 of these were used for determination of the water retention curves and the remaining 4 were used for determination of soil bulk density, ρ. Additionally, about 1 kg of loose soil was collected from each horizon for determination of the particle size distribution and content of organic matter.

The particle size distributions of the soil were measured by the sedimentation (hydrometer) method. The contents of organic matter were measured by wet oxidation. The particle size distributions were used to put the soils into the appropriate FAO/USDA soil texture classes.

Water retention was determined by first saturating the samples and then de-watering them on sand table apparatus for suctions of 10, 20, 40 and 80 hPa, on a kaolin table for a suction of 250 hPa, and on ceramic pressure plate extractors for applied air pressures of 500, 1 000, 2 000, 4 000, 8 000 and 15 000 hPa. There were two replicate samples for each suction/pressure for each soil horizon. Sample heights were 50 mm for the smallest 4 suctions, 25 mm for a suction of 250 hPa and 10 mm for samples in the pressure plate extractors. Samples were left to de-water for 2 days on the sand table, for 1 week on the kaolin table and for 2 weeks in the pressure plate extractors.

After these times, the samples were weighed, dried in an oven at 105°C for 48 h, and then re-weighed. Weighings were done using a 3-decimal place digital balance. Gravimetric water contents, *w*, were then calculated. The arithmetic mean values were calculated for the two replicate samples at each suction/pressure. The samples for determination of bulk density, ρ, were dried and weighed in a similar way.

The procedures of sample collection, analysis and measurement of water retention characteristics continued over a period of several years.

The water retention data ($w = \mathrm{f}(P_a)$) were fitted to the double-exponential (*DE*) Eq. (1) for the immiscible displacement case. Here, P_a is the air pressure applied in the pressure plate extractors, *C* is the residual water content, A_1 and A_2 are the amounts of textural and structural pore space, respectively, measured as gravimetric water contents at saturation, and P_1 and P_2 are applied air pressures characteristic for displacement of water from the textural and structural pore spaces, respectively. C, A_1, A_2, P_1 and P_2 are five adjustable fitting parameters. We recall the rule-of-thumb that experimental data are needed for at least twice as many values of P_a as there are adjustable parameters in order to get statistically-significant fits to the data. Our data with 11 different values of P_a meets this requirement:

$$w = C + A_1 \exp\left(\frac{-P_a}{P_1}\right) + A_2 \exp\left(\frac{-P_a}{P_2}\right). \tag{1}$$

It is important to note that we use applied air pressure, P_a (hPa), rather than the pore water suction, *h* (hPa). This is to remind us that pore water suction when samples are removed from a pressure plate apparatus is equal to the air pressure that was applied only in cases where thermodynamic equilibrium has been attained.

For the case in which thermodynamic equilibrium has been attained by diffusion of water, we use the Groenevelt and Grant (2004) equation (the GG equation):

$$w = k_1\left[\exp\left(\frac{-k_0}{(pF_0)^n}\right) - \exp\left(\frac{-k_0}{(pF)^n}\right)\right]. \tag{2}$$

In this case, the water retention curve is given by $w = f(pF)$. Here $pF = \log h$, where h is in units of hPa. The value $pF_0 = 6.653$ is the value of pF at which the soil water content becomes zero as discussed above. We assume that this value is also true for the soils investigated here. The adjustable parameters in Eq. (2) are: k_1, k_0 and n.

The curve-fitting for both Eqs (1) and (2) was done using the Levenberg-Marquardt algorithm (Marquardt, 1963) as implemented in the non-linear curve fitting routine in the Origin©7.0 computer program (OriginLab Corporation, Northampton, MA, USA).

Equation (2) was inverted to give pF as a function of water content, w. However, we want to know the pore water suction at the point of hydraulic cut-off. This occurs at the point where the residual water content, C, intercepts with the Groenevelt and Grant (2004) retention curve. This gives the value of pF_{hco} at hydraulic cut-off as shown in Eq. (3):

$$pF_{hco} = \exp\left[\left(\frac{1}{n}\right)\ln\left\{\frac{-k_0}{\ln\left[\exp\left(\frac{-k_0}{(pF_0)^n}\right) - \frac{C}{k_1}\right]}\right\}\right]. \tag{3}$$

The value of pF_{hco} was calculated using Eq. (3) for the 52 Polish soils.

RESULTS AND DISCUSSION

The results of the soil textural analysis are summarized in Table 1. This shows that the soils investigated have only small contents of clay, which reflects the sandy nature of the most Polish soils. The mean content of clay was 9.8 kg 100 kg^{-1} (min = 2, max = 25); the mean content of organic matter was 1.21 kg 100 kg^{-1} (min = 0.03, max = 2.46); and the mean bulk density was 1.57 Mg m^{-3} (min = 1.24, max = 1.81).

The values of residual water content, C, were positively correlated with the clay content of the soil as shown in Fig. 2. This can be summarized with the regression Eq. (4):

$$C = 0.0232 + 0.00369\,\text{clay},\ \text{kg kg}^{-1},\ r = 0.846,\ p<0.0001$$
$$(\pm 0.0039)\ (\pm 0.00033)\,. \tag{4}$$

Equation (4) may be compared with Eq. (17) in Dexter *et al.* (2012):

$$C = 0.0285 + 0.00336\,\text{clay},\ \text{kg kg}^{-1},\ r = 0.966,\ p<0.0001$$
$$(\pm 0.0041)\ (\pm 0.00026). \tag{5}$$

T a b l e 1. Number of instances of soil texture classes in the data set used in the experiments

FAO/USDA texture class	Number of instances
Clay	0
Sandy clay	0
Silty clay	0
Clay loam	0
Silty clay loam	0
Sandy clay loam	1
Loam	1
Silty loam	20
Silt	2
Sandy loam	19
Loamy sand	9
Sand	0
Total	52

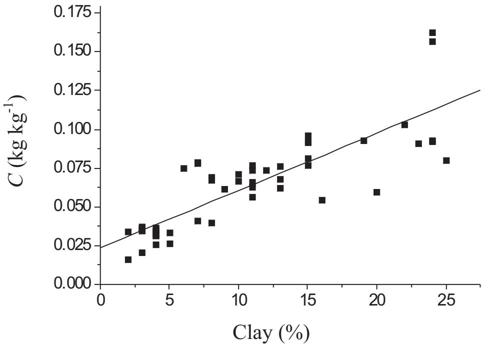

Fig. 2. Regression of values of the residual water content, C (kg kg^{-1}), obtained by fitting the double exponential (*DE*) Eq. (1) to water retention data for the 52 Polish soil horizons.

Equation (5) was obtained using a different data set from 14 soils (7 French and 7 Polish) having a wider range of clay contents (2-33 kg 100 kg^{-1}), and measured in two different laboratories. The coefficients in Eqs (4) and (5) are not statistically different, and both of these equations give similar predictions for C.

A casual observation of Fig. 2 might suggest a non-linear relationship between C and clay content. However, a quadratic term introduced into Eq. (4) did not have a coefficient significantly different from zero and the resulting equation had a smaller regression coefficient (r = 0.72). We therefore concluded that Eq. (4) is optimum for this data set.

Table 2 shows values of *PWP* for the different FAO/USDA soil texture classes calculated using Eq. (4) and the assumption that *PWP* = *C*, and using representative values for clay content and soil bulk density as given by Dexter (2004).

Table 2. Estimated values of PWP for the 12 FAO/USDA soil texture classes together with the representative values of clay content (clay) and bulk density (ρ) used in their calculation. Values of PWP are given both gravimetrically from Eq. (4) and volumetrically using the equation PWP (m^3 m^{-3}) = PWP (kg kg^{-1}) (ρ/ρ_w), where: ρ_w is the density of water. Values of PWP (kg kg^{-1}) are more accurate because they are independent of estimated values of ρ

FAO/USDA texture class	Particle size distribution		ρ	PWP	
	Clay	Silt			
	(kg 100 kg^{-1})		(Mg m^{-3})	(kg kg^{-1})	(m^3 m^{-3})
Clay	60	20	1.249	0.246	0.307
Sandy clay	42	7	1.334	0.179	0.239
Silty clay	47	47	1.309	0.198	0.259
Clay loam	34	34	1.376	0.150	0.206
Silty clay loam	34	56	1.376	0.150	0.206
Sandy clay loam	27	13	1.414	0.124	0.175
Loam	17	41	1.474	0.086	0.127
Silty loam	14	66	1.492	0.075	0.122
Silt	5	87	1.552	0.042	0.065
Sandy loam	10	28	1.518	0.061	0.092
Loamy sand	4	13	1.559	0.038	0.060
Sand	3	3	1.560	0.035	0.054

The mean value of pF_{hco} at the point of hydraulic cut-off calculated using Eq. (3) was found to be:

$$pF_{hco} = 4.012 \pm 0.015 \qquad (6)$$

where: the value of 0.015 is the standard error *ie* the standard deviation of the mean. The spread of values of pF_{hco} was remarkably small having a standard deviation of 0.109. The mean value given in Eq. (6) corresponds to a value of pore water suction at hydraulic cut-off:

$$h_{hco} = 1.03 \text{ MPa}. \qquad (7)$$

No statistically-significant correlation was found between pF_{hco} and any of the soil properties: clay content, organic matter content and bulk density. This is in contrast to Czyż and Dexter (2012) who found a weak correlation between pF_{maxc} (similar to pF_{hco}) and clay content. However, their data set included soils with a wider range of clay contents.

In order to illustrate the concepts introduced above, we have taken examples of results from the literature. These are shown in Figs 3-5. It is important to understand that these figures are to show concepts only, and the values used for different soils and plants are for illustration purposes only. We have to introduce one additional plant property for this discussion: it is the maximum suction that a plant root can generate to extract water from its surroundings. We call this h_r where the subscript r stands for root.

Figure 3 illustrates the situation described by Briggs and Shantz (1912) and by Veihmeyer and Hendrickson (1928). These researchers did very careful experiments and found that when different plant species wilted, then the value of soil water content remaining (PWP) was constant for a given soil. This clearly showed that wilting could be a soil property. They did not know the water suctions involved because methods to measure them had not yet been developed.

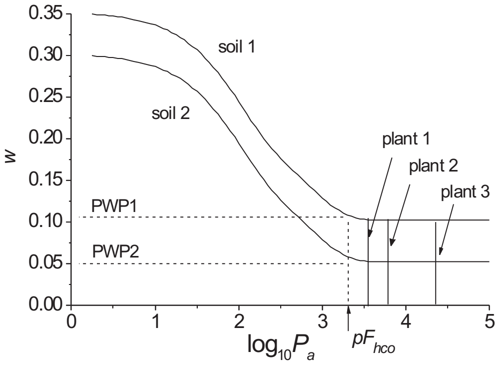

Fig. 3. Illustration of the situation described by Briggs and Shantz (1912) and Veihmeyer and Hendrickson (1928) where different plant species wilt at the same value of water content (PWP) in a given soil. Here, this situation is shown with 3 plant species in two different soils.

Figure 4 illustrates the finding of Richards and Weaver (1943) who used a pressure cell extractor with the objective of estimating the pore water suction when plant wilting occurred. They assumed, following Richards (1941), that the pore water suction in soil samples when they are removed from a pressure cell is numerically equal to the air pressure that was applied. We have shown (Czyż and Dexter,

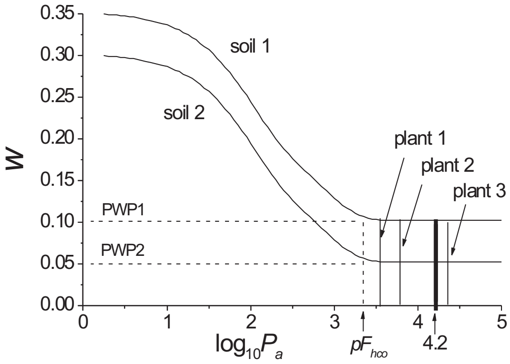

Fig. 4. Illustration of the situation described by Richards and Weaver (1943). Here, different plant species wilt at the same value of soil water content (*PWP*) as produced by a pressure cell apparatus working at a pressure of 1.5 MPa with the same soil (note: when this value is converted into hPa, the logarithm is equal to 4.2). The two different soils produce different values of *PWP*.

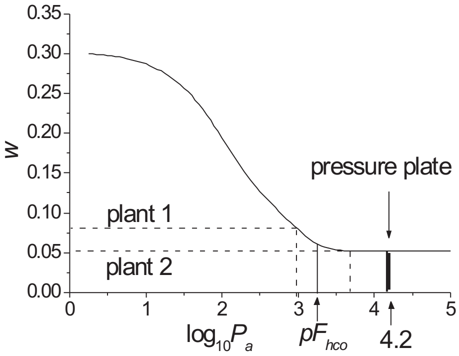

Fig. 5. Illustration of the situation described by Tolk (2003). In this case, plant species 2 (in this case corn (*Zea mays* L.)) wilted at the same value of soil water content as was produced by a pressure cell working at 1.5 MPa pressure. In contrast, plant species 1 (grain sorghum (*Sorghum bicolor* L.)) left more water *ie* had a larger *PWP* in the same soil.

2012; Dexter *et al.*, 2012) that this is not true in general. These quantities are equal only when thermodynamic equilibrium has been achieved in the pressure cell *ie* all the water has the same value of free energy, and this occurs only along the curve section WX in Fig. 1. In soil, either in a pressure cell or around a plant root, water moves by immiscible displacement. In this case, water movement can stop as a result of hydraulic cut-off, thermodynamic equilibrium is not attained and the resulting soil water suction is not equal to the pressure applied. This effect can result in the roots of different plant species producing the same value of *PWP* as described above. A pressure cell extractor working at 1.5 MPa, for example, would also produce the same value of water content. Richards and Weaver (1943) obtained this result with 109 of the 133 soils *ie* 82% of the soils that they investigated. However, this does not demonstrate any connection between the residual water content, *C*, or the *PWP* and the air pressure applied in the pressure cell. The similarity of values of the residual water content, *C*, and *PWP* has been wrongly interpreted as showing that plants wilt at a value of pore water suction of 1.5 MPa. This is usually not true. Instead, the similarity of these values provides supporting evidence for the horizontal nature of the curve section XZ in Fig. 1.

Figure 5 shows a simplified representation of the results of Tolk (2003) who found that the *PWP* of grain sorghum (*Sorghum bicolor* L.) was similar to the residual water content, *C*, of samples that had been de-watered in a pressure cell at an air pressure of 1.5 MPa. This is similar to the results shown in Fig. 4 and discussed above. However, for corn (*Zea mays* L.), wilting occurred at a larger water content ($PWP > C$) and at a smaller value of pore water suction ($h_r < h_{hco}$). Therefore, for the grain sorghum, $h_r > h_{hco}$. For the pressure cell samples, the suction of the remaining pore water was $h = h_{hco}$ irrespective of the air pressure applied. We conclude that in the clay loam soil used by Tolk (2003), wilting of sorghum was soil-limited and wilting of corn was plant-limited.

As a result of this study, we can recommend that any future work should include soils with a wider range of clay contents (perhaps up to 60 kg 100 kg^{-1}) in combination with several different plant species.

CONCLUSIONS

1. The evidence suggests that, in most cases plant wilting is caused by hydraulic cut-off in the soil. This is a soil property, not a plant property.

2. The suction of the pore water remaining in soil after hydraulic cut-off does not appear to be correlated with any one soil property. Therefore its prediction with pedotransfer functions is not possible with our current knowledge.

3. With our data set for 52 soil horizons, the mean predicted value of pore water suction at hydraulic cut-off is 1.03 MPa. In most cases, this will be the potential of the water remaining in soil after plants have wilted.

4. When plants wilt at water suctions smaller than the hydraulic cut-off suction, then the wilting is plant-limited. When plants wilt at suctions greater than the hydraulic cut-off suction, then the wilting is caused by hydraulic cut-off and is soil-limited.

5. The findings of Richards and Weaver (1943) interpreted as above show that plant wilting is soil-limited in 82% of cases.

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