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# 1 Prediction of water retention properties of Syrian clayey soils

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## 15 **ABSTRACT**

16 Studies on clayey soils developed in temperate areas have shown that their water retention properties  
17 are related to both the clay content and the specific pore volume of the clay, the latter being related to  
18 the hydric history of the soil. Our objective was to discuss the validity of these results for clayey soils  
19 developed in semi-arid areas. Samples were collected in soils located in Syria. Physico-chemical  
20 properties were determined. Water content was measured at field capacity and for water potentials  
21 ranging from  $-10$  to  $-15000$  hPa. X-ray diffraction analyses were performed on the clay fraction to  
22 identify the clay. Results showed that the clays have both a high cation exchange capacity (0.707 to  
23 0.891 mmol+ per g of clay) and a high external specific surface area (112 and 178 m<sup>2</sup> per g of clay).

24 These values are consistent with the X-ray diffraction results which showed the presence of a high  
25 proportion of smectite in most horizons and secondarily of varying proportions of illite and chlorite;  
26 kaolinite, while present, was not abundant. Results also showed that the amount of water retained by  
27 the clay according to the water potential was closely related to the specific pore volume of the clay at  
28 field capacity. Regression equations established by using both the data published earlier and those of  
29 this study enabled us to predict the water retention properties of clayey soils for a larger range of clay  
30 mineralogy and climatic environments including semi-arid environments than previously discussed in  
31 the literature.

32

33 **Keywords:** Clay content, Bulk density, Cation exchange capacity, Specific surface area, X-ray  
34 diffraction, Pedotransfer function.

35

## 36 **Introduction**

37 Clayey soils are often intensively cultivated in semi-arid and arid areas, particularly when irrigation is  
38 available (e.g., Ethan & Umar 2001; Mason et al., 2015). Their physical properties are closely related  
39 to the clay content and clay characteristics such as their mineralogical nature, the size of the  
40 elementary clay particles and the nature of the exchangeable cations (Tessier & Pédro 1987; Quirk  
41 1994; Wilson 1999; Churchman & Velde 2019). Whatever the soil texture and more markedly in semi-  
42 arid and arid areas, it is important to ascertain the water retention properties of soils in order to manage  
43 the water supply and consequently crop growth appropriately (Gaiser et al., 2000). To accomplish this,  
44 pedotransfer functions that enable prediction of the water retention properties of soils have therefore  
45 been developed (e.g., Bouma & Van Lanen 1987; Wösten et al., 1999; Al Majou et al., 2008a &  
46 2008b; Ostovari et al., 2015; Kalumba et al., 2020; Singh et al., 2020; Xu Xu et al., 2021), with several  
47 studies focusing on soils of semi-arid and arid areas (Tóth et al., 2012; Khlosi et al., 2012 & 2016; Al  
48 Majou et al., 2018; De Paepe et al., 2018; Santra et al., 2018; Dharumarajan et al., 2019; Soleimani et

49 al., 2020). At the same time, some studies aimed at a better understanding of the water retention  
50 properties of soils according to the characteristics of their clay minerals but the validity of the results  
51 for soils of semi-arid and arid areas remains unclear (Gaiser et al., 2000; Moret-Fernandez et al.,  
52 2013). For clayey soils developed on sedimentary materials, Bruand and Tessier (2000) showed that  
53 relationships between water retention properties and clay particles characteristics can be established.  
54 The clay particles, thanks to their fine size ( $< 2\mu\text{m}$ ), play a privileged role in water retention and soil  
55 structuring but also in the retention and bioavailability of chemical elements essential for plants  
56 (Bergaya & Lagaly 2013; Churchman & Velde 2019). Depending on the characteristics of clay  
57 particles, i.e. both their size and shape, the nature of the cations in the interlayer space and on the  
58 external surfaces, the clay fabric, which corresponds to both the volume of clay particles and the  
59 associated pore volume resulting from their assemblage, can vary highly from one soil to another, with  
60 significant consequences for the water retention properties of the soil (Tessier et al., 1992; Bruand &  
61 Tessier, 2000; Boivin et al., 2004). However, most studies on the water retention properties of clayey  
62 soils were developed for clayey soils in temperate areas and their validity for clayey soils in other  
63 climate areas is still under discussion. D'Angelo et al. (2014) studied the high sensitivity to drought of  
64 Chinese red clay soils developed on clayey sediments in humid subtropical areas. They showed that it  
65 was related to a very dense clay fabric which resulted from a high degree of consolidation, leading to a  
66 small porosity able to retain water available for plants. Other clayey soils in tropical and subtropical  
67 areas exhibit a strong micro-granular structure and their water retention properties are closely related  
68 to both inter- and intra-microgranular porosity (Balbino et al., 2004; Tawornpruek et al., 2005; Reatto  
69 et al., 2007). In this study, the objective was to analyze the water retention properties of clayey soils  
70 developed in semi-arid areas of Syria and to show how results recorded in earlier work on soils located  
71 in temperate areas (Bruand & Zimmer, 1992; Bruand & Tessier, 2000; Al Majou et al., 2008a) can be  
72 applied to the soils studied. We discuss how both the clay content and pore volume developed by the  
73 clay fabric, the latter being related to clay mineralogy and size of the elementary clay particles as well  
74 as the hydric history, can be used to predict the water retention properties of the clayey soils studied.

75

## 76 **Materials and methods**

### 77 *The soils studied*

78 The soils studied are located in semi-arid areas of Syria (Rigot 2006) between latitudes 32 and 41° N  
79 and longitudes 35 to 42° E. A set of 10 samples (clay content > 0.3 g g<sup>-1</sup>) including 4 horizons A and 6  
80 horizons B were collected in 5 clayey soils located in the vicinity of the towns of Jabah (JB 1 and  
81 JB 2), Al-Suwayda (SW 1), Al-Tha'Ala (TH 1) and Al-Qamishli (QM 1) (Table 1). The soils  
82 developed on clayey surface formations including coarse elements of basic extrusive rocks or  
83 calcareous alluvium parent materials (Table 1). They are Cambisols (JB 1 and JB 2), Vertisols (SW 1  
84 and TH 1) and a Clacisol (QM 1) according to the IUSS Working Group WRB (2015) (Tableau 1) and  
85 all Inceptisols according to the USDA Soil taxonomy (Soil Survey Staff, 2010) (Table 1). They are  
86 representative of the major Syrian clayey soils (Land Classification and Soil Survey of the Syrian  
87 Arab Republic, 1982) in two Syrian agro-climatic areas as defined by Khlosi et al. (2012).

88

### 89 *Physico-chemical and hydric analyses*

90 Undisturbed roughly parallelepiped samples 500-800 cm<sup>3</sup> in volume were collected in winter when the  
91 soil was near to field capacity and as a consequence near maximum swelling. The samples were stored  
92 at 4-5°C to reduce biological activity and in sealed plastic containers to avoid water loss.

93 Part of the samples was air-dried and manually ground in a mortar to < 2 mm material. Particle-  
94 size distribution was measured using the pipette method after pretreatment with hydrogen peroxide  
95 and sodium hexametaphosphate (Robert & Tessier 1974). The CaCO<sub>3</sub> content (*CaCO*<sub>3</sub>, in g per g of  
96 oven-dried soil) was measured according to Dupuis (1969). Cation exchange capacity (*CEC*, in mmol<sub>+</sub>  
97 per g of oven-dried soil) and exchangeable cations (in mmol<sub>+</sub> per g of oven-dried soil) were measured  
98 using ammonium acetate buffered at pH 7.0, and organic carbon content (*OC*, in g per g of oven-dried  
99 soil) by oxidation using an excess amount of potassium bichromate in sulphuric acid controlled at

100 135°C (Baize, 2018). The N<sub>2</sub>-BET external specific surface area (*SSA*, in m<sup>2</sup> per g of oven-dried soil)  
101 was measured for the < 2 mm fraction dried at 105 °C (Fripiat et al., 1971).

102 Centimetric clods (5 to 10 cm<sup>3</sup>) were separated by hand from the stored decametric samples.  
103 Their water content at field capacity (*W<sub>fc</sub>*, in g of water per g of oven dried soil) and bulk density (*D<sub>b</sub>*)  
104 were measured using the kerosene method (Monnier et al., 1973). The gravimetric water content (*W*,  
105 in g of water per g of oven-dried soil) at water potentials, *h*, of -10, -33, -100, -330, -1000, -3300  
106 and -15000 hPa was measured using a pressure membrane or pressure plate apparatus. The clods were  
107 placed on a paste made of < 2 μm particles of kaolinite to establish continuity of water between the  
108 clods and the membrane or the porous plate of the apparatus (Bruand et al., 1996).

109 The mineralogical composition of the < 2 μm material of the horizons was determined by X-ray  
110 diffraction (XRD) using the air dried < 2 mm material. The clay fraction was collected using the  
111 sedimentation method at 20°C after mechanical dispersion and saturated with Mg<sup>++</sup> according to  
112 Robert and Tessier (1974). Oriented clay deposits were prepared on glass slides and studied using an  
113 X-ray diffractometer equipped with a Si(Li) solid detector to filter the Cu<sub>kα</sub> radiation ( $\lambda_{Cu_{k\alpha}} =$   
114 1.5418 Å) of a standard European type X-ray tube (40 kV, 40 mA). The XRD patterns were collected  
115 from 2 to 24° 2θ per step of 0.05° 2θ, on successively air-dried at 20°C, glycoled, heated to 150 and  
116 then 550°C oriented clay deposits (Robert & Tessier 1974; Bruand & Prost 1986).

117

### 118 ***Criteria used to evaluate the performance of the regression equations***

119 The performance of the regression equations established to predict the gravimetric water of the  
120 horizons was assessed using the mean error (*ME*), the standard deviation (*SD*) and the root mean  
121 square error (*RMSE*):

$$122 \quad ME = \frac{1}{l} \sum_{j=1}^l (W_{p,i,j} - W_{m,i,j}) \quad (1)$$

123 
$$SD = \left\{ \frac{1}{l} \sum_{j=1}^l [(W_{p,i,j} - W_{m,i,j}) - ME]^2 \right\}^{1/2} \quad (2)$$

124 
$$RMSE = \left\{ \frac{1}{l} \sum_{j=1}^l (W_{p,i,j} - W_{m,i,j})^2 \right\}^{1/2} \quad (3)$$

125 where  $W_{p,i,j}$  is the predicted gravimetric water content of the horizon at matric potential  $i$  for the  
 126 horizon  $j$ ,  $W_{m,i,j}$  is the measured gravimetric water content of the horizon at matric potential  $i$  for the  
 127 horizon  $j$ , and  $l$  is the number of horizons studied.

128 In the same way,  $ME$ ,  $SD$  and  $RMSE$  were calculated to evaluate the performance of the equations  
 129 used to predict the volumetric water content of the horizons as follows:

130 
$$ME = \frac{1}{l} \sum_{j=1}^l (\theta_{p,i,j} - \theta_{m,i,j}) \quad (4)$$

131 
$$SD = \left\{ \frac{1}{l} \sum_{j=1}^l [(\theta_{p,i,j} - \theta_{m,i,j}) - ME]^2 \right\}^{1/2} \quad (5)$$

132 
$$RMSE = \left\{ \frac{1}{l} \sum_{j=1}^l (\theta_{p,i,j} - \theta_{m,i,j})^2 \right\}^{1/2} \quad (6)$$

133 where  $\theta_{p,i,j}$  is the predicted volumetric water content of the horizon at matric potential  $i$  for the horizon  
 134  $j$ ,  $\theta_{m,i,j}$  is the measured volumetric water content of the horizon at matric potential  $i$  for the horizon  $j$ ,  
 135 and  $l$  is the number of horizons studied.

136 The values of  $ME$  and  $SD$  provide information on the estimation bias and precision, respectively.  
 137 The sign of  $ME$  indicates whether the prediction overestimated (positive) or underestimated (negative)  
 138 the value predicted. As for  $RMSE$ , it varies according to both the overall prediction bias and overall  
 139 prediction precision. The calculation of  $ME$  gives equal weight to all errors whereas  $RMSE$  assigns  
 140 more weight to larger errors than to smaller ones. The greater the difference between  $ME$  and  $RMSE$ ,  
 141 the more large errors there are. Thus, the best prediction performance is recorded when  $ME$  is as close  
 142 as possible to 0 and  $SD$  and  $RMSE$  are as small as possible, indicating the most unbiased and precise  
 143 prediction.

144

## 145 **Results**

### 146 *Physico-chemical characteristics*

147 The main characteristics of the studied samples are given in Table 2. The horizons studied showed  
148 very low or low  $\text{CaCO}_3$  content ( $\leq 0.06 \text{ g g}^{-1}$ ) except for the horizons QML 1-1 and 1-2 for which the  
149  $\text{CaCO}_3$  content was  $0.30$  and  $0.31 \text{ g g}^{-1}$ , respectively. The organic carbon content ranged from  $0.002$  to  
150  $0.008 \text{ g g}^{-1}$ , the highest organic carbon content being recorded for the horizons A. The clay content  
151 ( $CC$ , in  $\text{g per g}$  of oven-dried soil at  $105^\circ\text{C}$ ) ranged from  $0.43$  to  $0.69 \text{ g g}^{-1}$  between the different  
152 horizons studied but did not vary highly with depth in each soil (Table 2). The cation exchange  
153 capacity ( $CEC$ , in  $\text{mmol}_+$  per  $\text{g}$  of oven-dried soil at  $105^\circ\text{C}$ ) ranged from  $0.304$  to  $0.492 \text{ mmol}_+ \text{ g}^{-1}$ .  
154 The external specific surface area ( $SSA$ , in  $\text{m}^2$  per  $\text{g}$  of oven-dried soil at  $105^\circ\text{C}$ ) ranged from  $61$  to  
155  $91 \text{ m}^2 \text{ g}^{-1}$ .

156

### 157 *Clay mineralogy*

158 The XRD patterns of the clay extracted from the horizons studied showed (Figure 1) the presence of  
159 different types of clays (Robert & Tessier 1974; Bruand & Prost 1986; Moore & Reynold 1997):

- 160 – 1:1 clays which are kaolinite as shown by the peak at  $0.72 \text{ nm}$  which is similar at  $20^\circ\text{C}$ ,  $150^\circ\text{C}$   
161 and after treatment with ethylene glycol. The absence of a peak at  $0.72 \text{ nm}$  after heating to  
162  $550^\circ\text{C}$  confirmed the presence of kaolinite which is dehydroxylated at such a temperature;
- 163 – non-swelling 2:1 clays which are illite as shown by the peak at  $1.12\text{--}1.02 \text{ nm}$  at  $20^\circ\text{C}$  which  
164 did not change after treatment with ethylene glycol. After heating at  $550^\circ\text{C}$ , this peak shifted  
165 to  $1.01 \text{ nm}$ , indicating the closing of the magnesian interlamellar spaces;



- 166 – swelling 2:1 clays which are smectite as shown by the shift of the wide peak at 1.44–1.57 nm  
167 at 20°C to 1.72–1.77 nm after treatment with ethylene glycol because of the swelling of the  
168 interlamellar space due to intercalation of the ethylene glycol molecules. After heating at  
169 550°C, all the peaks recorded for higher values than 1.01 nm disappeared, indicating the  
170 closing of the magnesian interlamellar spaces due to the loss of the ethylene glycol molecules;
- 171 – 2:1/1 clays which are chlorites as shown by the peak at 1.42–1.47 nm similar at 20°C and after  
172 treatment with ethylene glycol. The remaining peak at 1.42 nm recorded after heating at  
173 550°C is indeed consistent with the presence of chlorites which are not dehydroxylated at such  
174 a temperature.

175 A semi-quantitative evaluation of the content in the different types of clays identified is given in Table  
176 3.

177

### 178 *Water retention properties*

179 The water retention properties showed a wide variety of water content between –10 and –15000 hPa  
180 matric water potential (Table 4). The smallest and highest water contents at field capacity were 0.262  
181 and 0.507 g g<sup>-1</sup>, respectively. This high variation in water content at field capacity was consistent with  
182 the water content recorded at –10 hPa which ranged from 0.328 to 0.540 g g<sup>-1</sup> and at –15000 hPa  
183 which ranged from 0.207 to 0.385 g g<sup>-1</sup>.

184

## 185 **Discussion**

### 186 *Physico-chemical characteristics and clay mineralogy*

187 As the soil horizons contained little organic carbon (Table 2), which is consistent with the soil organic  
188 matter dynamics in semi-arid areas (Mrabet, 2011; Schellekens et al., 2013), the contribution of

189 organic matter to the cation exchange capacity was considered as being negligible compared with the  
190 cation exchange capacity of the clay. Indeed, if we assume that the cation exchange capacity of the  
191 organic matter of the soil studied is equal to  $4 \text{ mmol}_+ \text{ g}^{-1}$  of organic carbon, which is a value among  
192 the highest values recorded in the literature (Schnitzer, 1978; Tate & Theng, 1980; Stevenson, 1982),  
193 the contribution of organic matter to the *CEC* would range from 0.008 to  $0.032 \text{ mmol}_+ \text{ g}^{-1}$  of oven  
194 dried soil for the horizons studied. Thus, the cation exchange capacity of the clay ( $CEC_{cl}$ , in  $\text{mmol}_+$  per  
195 g of oven-dried clay at  $105^\circ\text{C}$ ) was calculated as follows:

$$196 \quad CEC_{cl} = (CEC/CC) \quad (7)$$

197 with *CC* the clay content. Results showed that  $CEC_{cl}$  ranged from 0.707 to  $0.891 \text{ mmol}_+ \text{ g}^{-1}$  (Table 5),  
198 indicating that the clay fraction was mainly composed of swelling 2:1 clays (Robert & Tessier 1974;  
199 Wilson, 1999; Churchman & Velde 2019). These values of  $CEC_{cl}$  are consistent with the X-ray  
200 diffraction data (Figure 1) which show the predominance of 2/1 clay minerals with smectite content  
201 ranging from not abundant to abundant depending on the horizon (Table 3).

202 As the calculated surface area developed by quartz spheres with a diameter  $> 2 \mu\text{m}$  was  $< 1.1 \text{ m}^2$   
203  $\text{g}^{-1}$ , the contribution of both the silt and sand particles can be assumed to range from 0.2 to  $0.6 \text{ m}^2 \text{ g}^{-1}$   
204 for the soil studied and therefore negligible compared to the *SSA* measured (Table 2). Thus, the  
205 external specific surface area (*SSA*) of the clay fraction was calculated ( $SSA_{cl}$ ,  $\text{m}^2$  per g of oven-dried  
206 clay at  $105^\circ\text{C}$ ) as follows:

$$207 \quad SSA_{cl} = (SSA/CC) \quad (8)$$

208 The results showed that  $SSA_{cl}$  ranged from 112 to  $178 \text{ m}^2 \text{ g}^{-1}$  (Table 5) which are high external specific  
209 surface areas for clays, indicating a very small size of the elementary clay particles in the horizons  
210 studied (Bergaya & Lagaly 2013; Churchman & Velde 2019).

211 Compared to the 37 clayey soils studied by Bruand and Tessier (2000), the  $CEC_{cl}$  recorded for the  
212 Syrian clayey soils studied were higher. The  $SSA_{cl}$  recorded in this study were also higher than those  
213 recorded by Bruand and Tessier (2000) except for the horizons JB 1 and JB 2 for which the  $SSA_{cl}$  were

214 among the highest recorded by these authors. To extend the range of both the  $CEC_{cl}$  and  $SSA_{cl}$   
215 discussed, the relationship between  $CEC_{cl}$  and  $SSA_{cl}$  was established using both the data published by  
216 Bruand and Tessier (2000) and those recorded in this study (Figure 2). The closeness of the  
217 relationship ( $R^2 = 0.78$ ,  $n = 47$ ) is consistent with the results recorded by Bruand and Zimmer (1992)  
218 and Bigorre et al. (2000), indicating that a high proportion of  $CEC_{cl}$  variance was explained by  $SSA_{cl}$   
219 for the soils studied and consequently by the size of the elementary clay particles (Figure 2). Thus, the  
220 cation exchange capacity of the elementary clay particles appears to be mainly related to the negative  
221 charges present on the external surfaces of these particles (Robert et al., 1991; Bergaya & Lagaly  
222 2013). The high distance to the regression line recorded for the horizons TH 1-2, TH 1-3, QM 1-1 and  
223 QM 1-2 indicates that the interfoliar space of the elementary clay particles, which  $SSA_{cl}$  does not  
224 account for, contributes more than for the other horizons to their cation exchange capacity (Figure 2,  
225 Table 5) (Bergaya & Lagaly 2013; Churchman & Velde 2019).

226 Comparison of the XRD patterns with the values of  $CEC_{cl}$  and  $SSA_{cl}$  recorded showed the  
227 presence of a small amount of smectite for JB 2-1, JB 2-2 and JB 2-3 when  $CEC_{cl}$  and  $SSA_{cl}$  were  
228 among the highest values recorded (Figure 1, Tables 3 and 5). The low intensity of the peak between  
229 1.44 and 1.57 nm at 20°C and between 1.72 and 1.77 nm after treatment with ethylene glycol  
230 (Figure 1) is in all likelihood related to the weak organization along the crystallographic plane  $ab$  of  
231 the elementary clay particles in the clay deposit on the glass slide because of the very small size of the  
232 elementary clay particles as indicated by  $SSA_{cl}$  (Table 5) (Tessier & Pédro 1987). The proportion of  
233 smectite in JB 2-1, JB 2-2 and JB 2-3 is therefore probably higher than that indicated by the XRD  
234 patterns (Figure 1) and reported in Table 3.

235

### 236 ***Pore volume developed by the assemblage of elementary clay particles***

237 Assuming that water was mainly retained by the clay phase whatever the potential, as earlier shown by  
238 Bruand and Zimmer (1992), Bruand and Tessier (2000) and D'Angelo et al. (2014), we considered  
239 that for the centimetric clods at field capacity the volume of cracks and biopores was negligible

240 compared with the pore volume developed by the assemblage of the elementary clay particles. Thus,  
241 the specific volume of clods at the field conditions ( $V_{fc}$ ) is related to the specific volume of the solid  
242 phase ( $V_s$ , in  $\text{cm}^3$  per g of oven-dried soil) and to the specific pore volume ( $V_p$ , in  $\text{cm}^3$  per g of oven-  
243 dried soil) as follows:

$$244 \quad V_{fc} = V_s + V_p \quad (9)$$

245  $V_p$  was calculated for each horizon using  $V_s = 0.377 \text{ cm}^3 \text{ g}^{-1}$  which corresponds to a particle density of  
246 2.65 and  $V_{fc}$  which corresponds to the reciprocal of  $D_b$  measured on centimetric clods (Table 2),  
247 giving:

$$248 \quad V_p = (1/D_b) - V_s \quad (10)$$

249 The values of  $V_p$  recorded ranged from 0.671 to 0.840  $\text{cm}^3 \text{ g}^{-1}$ . The specific pore volume of the clay  
250 ( $V_{p,cl}$ , in  $\text{cm}^3$  per g of oven-dried clay) was calculated as follows:

$$251 \quad V_{p,cl} = V_p / CC \quad (11)$$

252 The quantity  $V_{p,cl}$ , which can be considered as a quantitative expression of the clay fabric, ranged from  
253 0.612 to 0.722  $\text{cm}^3 \text{ g}^{-1}$  (Table 5). This is a much smaller range of variation than that recorded for the  
254 soils studied by Bruand and Tessier (2000) ( $0.337 \leq V_{p,cl} \leq 1.484 \text{ cm}^3 \text{ g}^{-1}$ ). However, it is interesting to  
255 note that although the values of  $CEC_{cl}$  recorded for the Syrian clayey horizons studied are higher than  
256 those recorded for the clayey soils studied by Bruand and Tessier (2000), 6 soils of those studied by  
257 the latter showed higher  $V_{p,cl}$  than those recorded in this study, thus illustrating that  $V_{p,cl}$  varies  
258 according to the clay mineralogy but also according to the hydric history of the soil (Tessier and  
259 Pédro, 1984 and 1987). In the same way, even if  $V_{p,cl}$  could theoretically be assumed to be closely  
260 related to the size of the elementary clay particles, the results recorded showed the lack of a close  
261 relationship between  $V_{p,cl}$  and  $SSA_{cl}$ , again because of the hydric history of the soil (Tessier and Pédro,  
262 1984 and 1987). This is the case of the Syrian clayey soils studied with a very poor relationship  
263 between  $V_{p,cl}$  and  $SSA_{cl}$  ( $R^2 = 0.24$ ).

264

265 ***Water retention properties of the clay***

266 Since the difference in water retention properties between the horizons results from the variation in  
267 both the clay content and the water retention properties of the clay, the latter were calculated by  
268 correcting the gravimetric water content of the horizon ( $W$ ) for clay content ( $CC$ ) at different water  
269 potentials as follows:

270 
$$W_{cl} = W/CC \quad (12)$$

271 The quantity  $W_{cl}$  can be considered as the amount of water retained by the pore volume related to the  
272 clay fabric ( $W_{cl}$ , in g of water per g of oven-dried clay). Regression equations were established  
273 between  $W_{cl}$  and  $V_{p,cl}$  with the data published by Bruand and Tessier (2000) and then with both the data  
274 published by these authors and those recorded in this study for Syrian clayey soils (Table 6).

275 Although the range of variation of  $CEC_{cl}$  and  $SSA_{cl}$  was markedly different between, on the one  
276 hand, the dataset published by Bruand and Tessier (2000) with  $CEC_{cl}$  ranging from 0.227 to 0.666  
277  $\text{mmol}_+ \text{g}^{-1}$  and  $SSA_{cl}$  ranging from 53 to 139  $\text{m}^2 \text{g}^{-1}$  and, on the other hand, the Syrian dataset with  
278  $CEC_{cl}$  ranging from 0.707 to 0.891  $\text{mmol}_+ \text{g}^{-1}$  and  $SSA_{cl}$  from 112 to 178  $\text{m}^2 \text{g}^{-1}$  (Table 5), the  
279 regression equations established by Bruand and Tessier (2000) (Table 6) were tested with the Syrian  
280 dataset to be able to discuss the expected improvement in the prediction quality when the regression  
281 equations are established with both datasets (Table 7). Their performance was evaluated using  $ME$ ,  $SD$   
282 and  $RMSE$ . Results showed that  $ME$  ranged from  $-0.065 \text{ g g}^{-1}$  at  $-10 \text{ hPa}$  water potential to  $0.047 \text{ g g}^{-1}$   
283 at  $-1000 \text{ hPa}$  water potential (mean =  $-0.008 \text{ g g}^{-1}$ ),  $SD$  from  $0.042 \text{ g g}^{-1}$  at  $-15000 \text{ hPa}$  water potential  
284 to  $0.069 \text{ g g}^{-1}$  at  $-330 \text{ hPa}$  water potential (mean =  $0.057 \text{ g g}^{-1}$ ) and  $RMSE$  from  $0.051 \text{ g g}^{-1}$  at  $-3300$   
285  $\text{hPa}$  water potential to  $0.091 \text{ g g}^{-1}$  at  $-10 \text{ hPa}$  water potential (mean =  $0.068 \text{ g g}^{-1}$ ) (Table 7).

286 Regression equations were established between  $W_{cl}$  and  $V_{p,cl}$  using both the data recorded by  
287 Bruand and Tessier (2000) and the data recorded in this study (Table 6). They were tested successively  
288 on the two datasets by recalculating them each time without taking into account the horizon on which

289 they were tested. The number of horizons used to establish the regression equations was 46, one being  
290 left out when calculating each regression equation. When tested on the dataset published by Bruand  
291 and Tessier (2000), results showed that *ME* ranged from  $-0.011 \text{ g g}^{-1}$  at  $-330 \text{ hPa}$  and  $-1000 \text{ hPa}$   
292 water potential to  $0.014 \text{ g g}^{-1}$  at  $-10 \text{ hPa}$  water potential (mean =  $0.001 \text{ g g}^{-1}$ ), *SD* from  $0.035 \text{ g g}^{-1}$  at  $-$   
293  $3300 \text{ hPa}$  water potential to  $0.043 \text{ g g}^{-1}$  at  $-10 \text{ hPa}$  water potential (mean =  $0.039 \text{ g g}^{-1}$ ) and *RMSE*  
294 from  $0.035 \text{ g g}^{-1}$  at  $-3300 \text{ hPa}$  water potential to  $0.045 \text{ g g}^{-1}$  at  $-10 \text{ hPa}$  water potential according  
295 (mean =  $0.040 \text{ g g}^{-1}$ ) (Table 7). When tested on the Syrian clayey soils, results showed a lower  
296 prediction performance than when tested on the French dataset, with *ME* ranging from  $-0.052 \text{ g g}^{-1}$  at  
297  $-10 \text{ hPa}$  water potential to  $0.037 \text{ g g}^{-1}$  at  $-1000 \text{ hPa}$  water potential (mean =  $-0.006 \text{ g g}^{-1}$ ), *SD* from  
298  $0.043$  at  $-15000 \text{ hPa}$  water potential to  $0.070 \text{ g g}^{-1}$  at  $-330 \text{ hPa}$  water potential (mean =  $0.058 \text{ g g}^{-1}$ ) and  
299 *RMSE* from  $0.050 \text{ g g}^{-1}$  at  $-3300 \text{ hPa}$  water potential to  $0.083 \text{ g g}^{-1}$  at  $-10 \text{ hPa}$  water potential (mean =  
300  $0.065 \text{ g g}^{-1}$ ) (Table 7). Comparison of these values with those recorded when the regression equations  
301 were established with the data of Bruand and Tessier (2000) showed that the range of bias for water  
302 potential ranging from  $-10$  to  $-15000 \text{ hPa}$  was reduced by 20%, with no variation in the precision  
303 when the regression equations were established with both the datasets (Table 7). The overall  
304 prediction quality was slightly increased, as indicated by the *RMSE* values which were reduced by  
305 20% when the regression equations were established using both datasets (Table 7).

306 Thus, when clayey soils with clays developing a high CEC and a hydric history acquired in a  
307 semi-arid climate are taken into account, this slightly improves the validity of using  $V_{p,cl}$  to predict the  
308 water retention properties of the clay of horizons belonging to soils developed under a larger range of  
309 climatic environments than those already studied in the literature.

310

### 311 ***Water retention curve of the horizons***

312 The regression equations established between  $W_{cl}$  and  $V_{p,cl}$  make it possible to predict the water  
313 content at the scale of the horizon since:

314 
$$W_i = CC \times [a_i + (b_i \times V_{p,cl})] \quad (13)$$

315 with  $W_i$ , the gravimetric water content in g of water per g of oven-dried soil at the water potential  $i$ ,  
 316  $CC$ , the clay content of the soil in g of clay per g of oven-dried soil,  $a_i$  and  $b_i$ , the coefficients of the  
 317 regression equations at the water potential  $i$  (Table 6), and  $V_{p,cl}$ , the specific pore volume of the clay in  
 318  $\text{cm}^3$  per g of oven-dried clay for the soil at field capacity. The predicted volumetric water content at  
 319 water potential  $i$  ( $\theta_i$ , in  $\text{cm}^3$  of water per  $\text{cm}^3$  of soil) can be calculated as follows:

320 
$$\theta_i = D_b \times W_i. \quad (14)$$

321 Then, by using equations (7), (8) and (11):

322 
$$\theta_i = D_b \times CC \times \{a_i + [b_i \times ((1/D_b) - V_s)/CC]\} \quad (15)$$

323 which becomes:

324 
$$\theta_i = D_b \times CC \times \{a_i + [b_i \times ((1/D_b) - 0.377)/CC]\} \quad (16)$$

325 using  $V_s = 0.377 \text{ cm}^3 \text{ g}^{-1}$  which corresponds to a particle density of 2.65. The  $\theta_i$  calculated at the  
 326 different water potentials and for the different horizons were compared to the  $\theta_i$  measured. Results  
 327 showed  $ME$  ranging from  $-0.028 \text{ cm}^3 \text{ cm}^{-3}$  at  $-33 \text{ hPa}$  water potential to  $0.025 \text{ cm}^3 \text{ cm}^{-3}$  at  $-1000 \text{ hPa}$   
 328 water potential (mean =  $-0.005 \text{ cm}^3 \text{ cm}^{-3}$ ),  $SD$  from  $0.036 \text{ cm}^3 \text{ cm}^{-3}$  at  $-15000 \text{ hPa}$  water potential to  
 329  $0.054 \text{ cm}^3 \text{ cm}^{-3}$  at  $-10$  and  $-33 \text{ hPa}$  water potential (mean =  $0.046 \text{ cm}^3 \text{ cm}^{-3}$ ) and  $RMSE$  from  $0.039$   
 330  $\text{cm}^3 \text{ cm}^{-3}$  at  $-3300 \text{ hPa}$  water potential to  $0.059 \text{ cm}^3 \text{ cm}^{-3}$  at  $-33 \text{ hPa}$  water potential (mean =  $0.048$   
 331  $\text{cm}^3 \text{ cm}^{-3}$ ) (Table 8).

332 These results can be compared with those recorded earlier with soils located in semi-arid areas.  
 333 Tombul et al. (2004) applied early pedotransfer functions established using multiple linear regression  
 334 to 126 horizons originating from soils developed in a semi-arid area in Turkey. They compared the  
 335 measured and predicted volumetric water contents at  $-330$  and  $-15000 \text{ hPa}$  and recorded a mean  
 336  $RMSE$  of  $0.072$  and  $0.030 \text{ cm}^3 \text{ cm}^{-3}$ , respectively. Mosaddeghi and Mahboubi (2011) studied the water

337 retention properties of 63 soils located in a semi-arid area of western Iran. They developed  
338 pedotransfer functions using multiple linear regression and the comparison of the measured and  
339 predicted volumetric water content at 11 water potentials between  $-10$  and  $-15000$  hPa led to *RMSE*  
340 ranging from  $0.034$  to  $0.044 \text{ cm}^3 \text{ cm}^{-3}$  for the 63 topsoils and from  $0.034$  to  $0.047 \text{ cm}^3 \text{ cm}^{-3}$  for the  
341 subsoils. More recently, Dharumarajan et al. (2019) established pedotransfer functions using also  
342 multiple linear regression for soils developed in a semi-arid area of India. They studied 740 horizons  
343 originating from 149 soils with varying textures. The *RMSE* recorded when they compared the  
344 measured and predicted volumetric water content at  $-330$  and  $-15000$  hPa was  $0.046$  and  $0.032$   
345  $\text{cm}^3 \text{ cm}^{-3}$ , respectively.

346 Using multiple linear regression, artificial neural networks and support vector machines, Khlosi et  
347 al. (2016) discussed the performance of pedotransfer functions established with Syrian soils which  
348 were mainly loam, clay loam and clay soils. They applied their pedotransfer functions to 18 horizons  
349 originating from Syrian soils and recorded values of *RMSE* higher than those recorded in this study  
350 with *RMSE* ranging from  $0.065$  to  $0.089 \text{ cm}^3 \text{ cm}^{-3}$  (mean =  $0.080 \text{ cm}^3 \text{ cm}^{-3}$ ) with multiple linear  
351 regressions, from  $0.055$  to  $0.075 \text{ cm}^3 \text{ cm}^{-3}$  (mean =  $0.067 \text{ cm}^3 \text{ cm}^{-3}$ ) with artificial neural networks and  
352 from  $0.048$  to  $0.064 \text{ cm}^3 \text{ cm}^{-3}$  (mean =  $0.058 \text{ cm}^3 \text{ cm}^{-3}$ ) with support vector machines.

353 As the size of the datasets used in these different studies was highly variable and larger than in our  
354 study, the comparison with our results and between the different studies remains limited to the  
355 observation that the *RMSE* values are of the same order of magnitude. In our study, we used only two  
356 soil characteristics, the clay content and the bulk density when the soil was close to field capacity,  
357 when the above studies have used much more soil characteristics. Our results indicate for soils of  
358 semi-arid areas the interest of developing pedotransfer functions which take variables closely related  
359 to the water retention mechanisms in soils more into account. The values of  $\theta$  calculated with the  
360 proposed equations at the different water potentials can be used to fit a model of water retention curve  
361 which is usually required to predict plant-available water and more generally, to run plant-soil-water  
362 models. Future work will aim at enlarging both the range of textures and of climatic conditions under



363 which the clayey soils developed, with the aim of studying the way in which their water retention  
364 properties are related to the hydric history.

365

## 366 **Conclusion**

367 Our objective was to analyze the water retention properties of clayey soils developed in semi-arid  
368 areas of Syria and to discuss how these properties could be explained by the characteristics of the clay.  
369 Results showed that the clay of the soils studied has both a higher cation exchange capacity and a  
370 higher external specific surface area than those recorded for clayey soils studied in temperate areas and  
371 used as a reference in this study. The cation exchange capacity and external specific surface area  
372 values recorded are consistent with the clay mineralogy, as shown by the X-ray diffraction data which  
373 revealed the presence in most horizons of a high proportion of smectite and secondarily a varying  
374 proportion of illite and chlorite, while kaolinite was present but not abundant. Results also showed that  
375 the amount of water retained by the clay at water potentials ranging from  $-10$  to  $-15000$  hPa was  
376 closely related to the specific pore volume developed by the elementary clay particles at field capacity.  
377 Thus, regression equations established by using both the data earlier published and those recorded in  
378 this study were proposed to predict the water retention properties of clayey soils over a larger range of  
379 clay mineralogies and climatic environments than previously reported in the literature. The specific  
380 pore volume as well as the clay content were found to be the most important predictors of water  
381 retention properties, the former corresponding to the pore volume developed by the elementary clay  
382 particles which varies according to the clay mineralogy and hydric history of the soil. Finally, from a  
383 more applied point of view, our results showed the significance of the bulk density measured in  
384 conditions close to the field capacity to predict the water retention properties of clayey soils. It should  
385 be more systematically measured during soil studies.

386

387

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392

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546



547 **List of Figures**

548

549 **Figure 1.** X-ray diagrams of oriented deposits of the clay material extracted from the clayey horizons  
550 studied under room conditions (20 °C), after saturation with ethylene-glycol (EG), after heating at 150  
551 °C and 550 °C.

552

553 **Figure 2.** Relation between the cation exchange capacity of the clay ( $CEC_{cl}$ ) and the specific surface  
554 area of the clay ( $SSA_{cl}$ ) for both the clayey soils studied by Bruand and Tessier (2000) (o) and the  
555 Syrian clayey soils of this study (●).

556

557

558 **List of tables**

559

560 **Table 1.** Main characteristics of the soils studied.

561

562 **Table 2.** Main characteristics of the horizons studied.

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564 **Table 3.** Semi-quantitative evaluation of clay minerals identified by DRX.

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566 **Table 4.** Water content at field conditions ( $W_{fc}$ , g g<sup>-1</sup>) and at different water potentials ( $W_h$ , g g<sup>-1</sup>).

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568 **Table 5.** Characteristics calculated for the clay of the Syrian soils studied.

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570 **Table 6.** Regression equations between the water content of clay ( $W_{cl}$ ) at different water potentials and  
571 the clay fabric ( $V_{p, cl}$ ) calculated with the data published in tables 1, 2 and 3 by Bruand and Tessier  
572 (2000).

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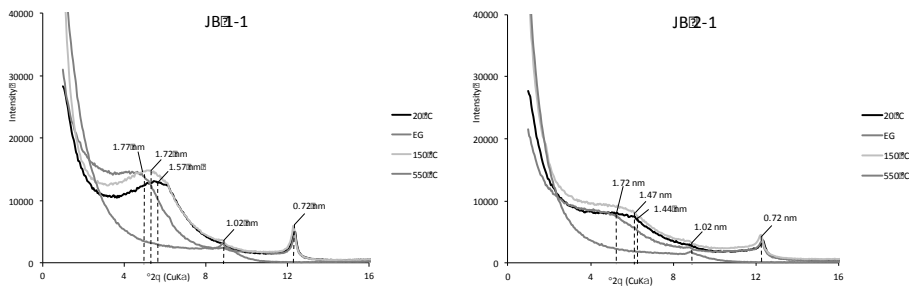
574 **Table 7.** Mean error of prediction ( $ME$ ), standard deviation ( $SD$ ) and root mean square error ( $RMSE$ )  
575 recorded with the regression equations established between the gravimetric water content of clay ( $W_{cl}$ ,  
576 in g g<sup>-1</sup> of oven dried clay) at different water potentials and the pore volume developed by the  
577 elementary clay particles ( $V_{p, cl}$ , in cm<sup>3</sup> g<sup>-1</sup> of oven dried clay) at field capacity.

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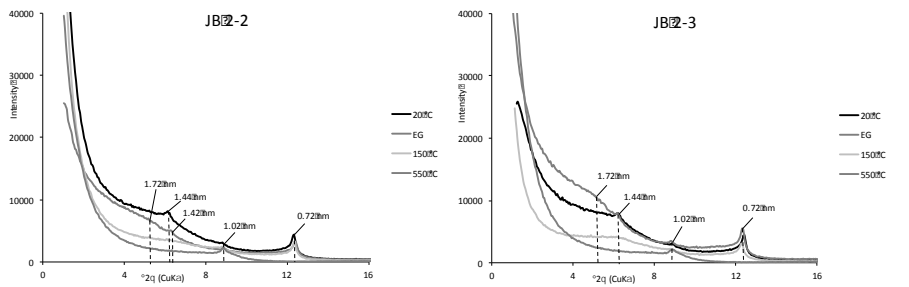
579 **Table 8.** Mean error of prediction ( $ME$ ), standard deviation ( $SD$ ) and root mean square error ( $RMSE$ )  
580 recorded with the regression equations established between the volumetric water content of clay ( $\theta_h$ , in  
581 cm<sup>3</sup> cm<sup>-3</sup>) at different water potentials  $h$  and both the clay content and the reciprocal of bulk density  
582 measured in conditions close to field capacity with both the data published by Bruand and Tessier  
583 (2000) and those recorded in this study when applied to the horizons of this study.

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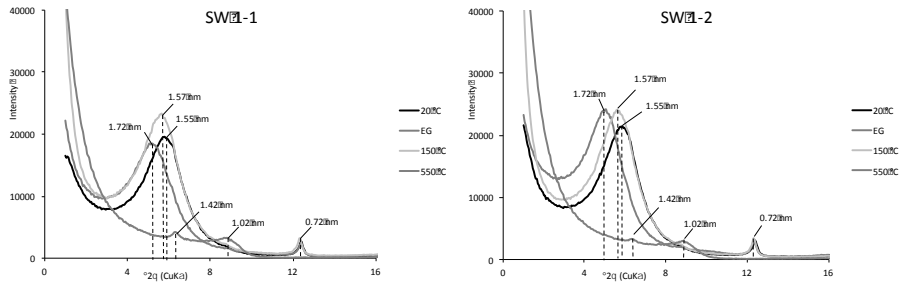
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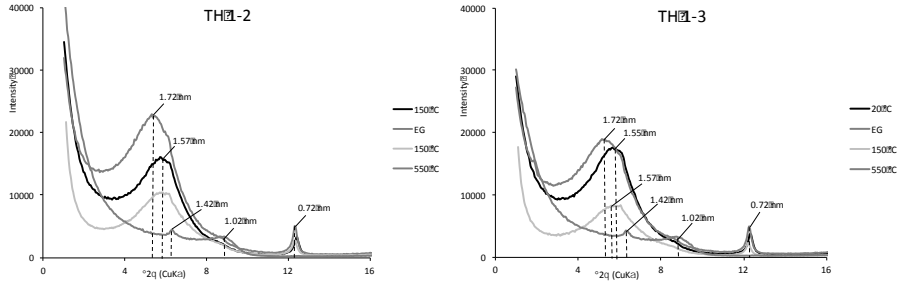
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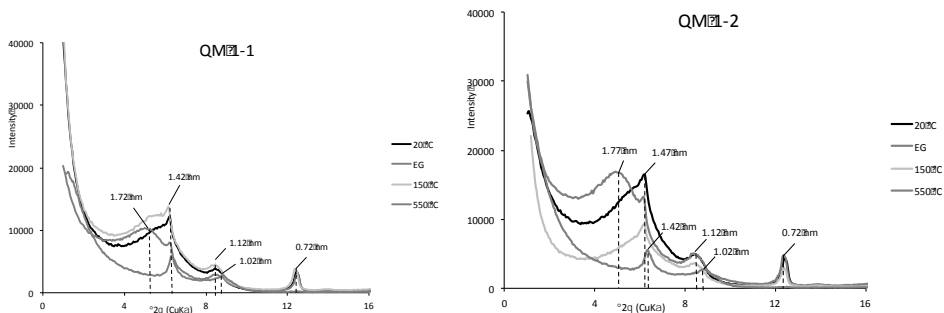
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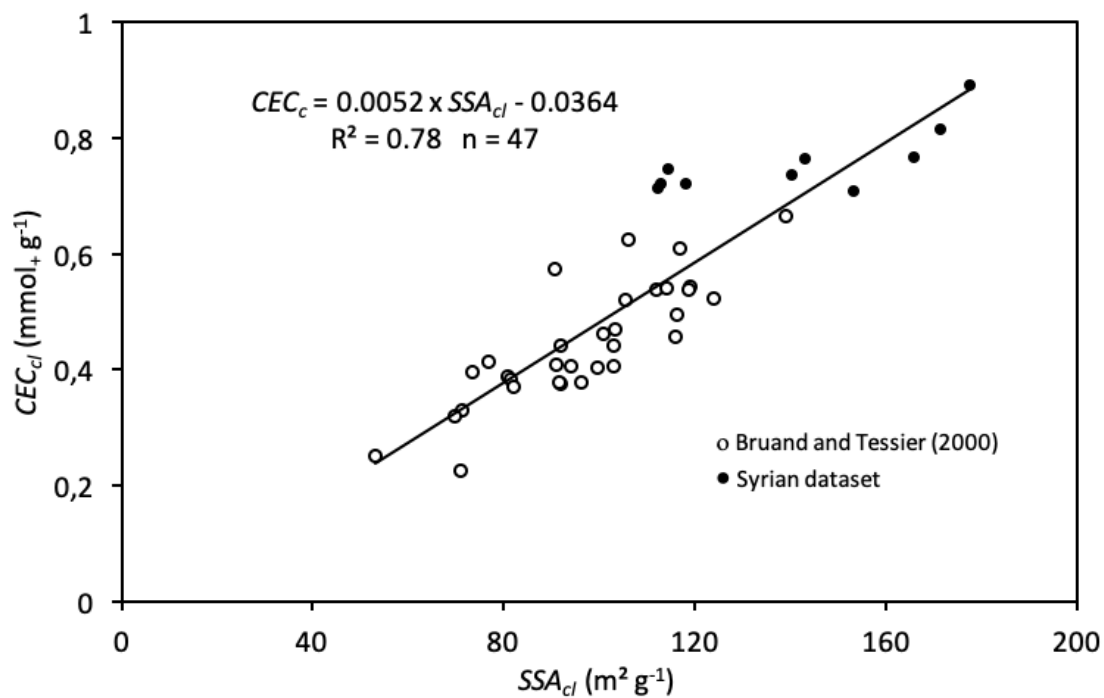
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591 **Figure 1.** X-ray diagrams of oriented deposits of the clay material extracted from the clayey horizons  
592 studied under room conditions (20 °C), after saturation with ethylene-glycol (EG), after heating at 150  
593 °C and 550 °C.

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597 **Figure 2.** Relation between the cation exchange capacity of the clay ( $CEC_{cl}$ ) and the specific surface  
598 area of the clay ( $SSA_{cl}$ ) for both the clayey soils studied by Bruand and Tessier (2000) (o) and the  
599 Syrian clayey soils of this study (●).

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604 **Table 1.** Main characteristics of the soils studied.

Soil location	Coordinates UTM	Soil type Soil Survey Staff (2010) / IUSS Working Group WRB (2015)	Parent material	Land use	Agro-climatic zone
Jabbah (JB 1)	33.1623N – 35.9368E	Typic Haploxerept / Hypereutric Cambisol		Meadow	1
Jabbah (JB 2)	33.1520N – 35.9243E	Typic Haploxerept / Hypereutric Cambisol	Clayey surface formations	Meadow	1
Al-Suwayda (SW 1)	32.7118N – 36.5494E	Vertic Chromoxerept / Chromic Vertisol	including coarse elements of basic extrusive rocks	Annual crops	2
Al-Tha'Ala (TH 1)	32.7115N – 36.4860E	Vertic Xerochept / Chromic Vertisol		Olive trees	2
Al-Qamishli (QM 1)	41.0324N – 41.1303E	Calcic Xerocept / Vertic Calcisol	Calcareous alluvium materials	Annual crops	1

605 Agro-climatic zones according to Khlosi et al. (2012): zone 1 is characterized by a mean annual precipitation >300 mm in 2 out of 3 seasons and shrubland, degraded forest, rock outcrops and  
606 permanent crops; zone 2 is characterized by a mean annual precipitation of 250-300 mm 2 out of 3 seasons, permanent crops and rainfed field crops with irrigated crops.

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611 **Table 2.** Main characteristics of the horizons studied.

Soil Sample	Horizon	Depth cm	Texture	$D_b$	Particle size distribution			$\text{CaCO}_3$ $\text{g}\cdot\text{g}^{-1}$	$OC$ $\text{g}\cdot\text{g}^{-1}$	$CEC$ $\text{mmol}_+\cdot\text{g}^{-1}$	Exchangeable cations				$SSA$ $\text{m}^2\cdot\text{g}^{-1}$
					$\text{g}\cdot\text{g}^{-1}$						$\text{mmol}_+\cdot\text{g}^{-1}$				
					Clay <2 $\mu\text{m}$	Silt 2- 50 $\mu\text{m}$	Sand 50- 2000 $\mu\text{m}$				$\text{Ca}^{2+}$	$\text{Mg}^{2+}$	$\text{Na}^+$	$\text{K}^+$	
JB 1-1	A	5-25	F	1.48	0.43	0.34	0.23	$\leq 0.01$	0.008	0.304	0.180	0.086	0.019	0.010	65.9
JB 2-1	A	5-25	F	1.49	0.45	0.29	0.26	$\leq 0.01$	0.008	0.345	0.202	0.099	0.020	0.010	74.7
JB 2-2	B	30-60	F	1.44	0.46	0.30	0.24	$\leq 0.01$	0.004	0.375	0.208	0.113	0.016	0.008	78.9
JB 2-3	B	60-80	F	1.41	0.46	0.31	0.23	0.02	0.002	0.410	0.209	0.116	0.010	0.007	81.7
SW 1-1	A	0-25	F	1.26	0.58	0.22	0.20	0.04	0.004	0.442	0.306	0.097	0.008	0.009	83.0
SW 1-2	B	30-70	VF	1.28	0.65	0.16	0.19	0.05	0.002	0.478	0.333	0.093	0.010	0.007	91.3
TH 1-2	B	25-50	VF	1.28	0.66	0.15	0.19	0.06	0.003	0.475	0.294	0.119	0.016	0.011	74.6
TH 1-3	B	50-75	VF	1.25	0.69	0.11	0.20	0.06	0.002	0.492	0.317	0.082	0.024	0.008	77.6
QM 1-1	A	0-25	F	1.32	0.53	0.25	0.22	0.30	0.006	0.395	0.290	0.082	0.010	0.005	60.8
QM 1-2	B	25-50	F	1.34	0.57	0.24	0.19	0.31	0.004	0.410	0.320	0.089	0.006	0.003	67.4
Mean	-	-	-	1.36	0.55	0.24	0.21	0.087	0.004	0.413	0.266	0.098	0.014	0.008	75.6
SD	-	-	-	0.09	0.09	0.08	0.03	0.111	0.002	0.058	0.059	0.014	0.006	0.002	8.6
Min	-	-	-	1.25	0.43	0.11	0.19	0.01	0.002	0.305	0.180	0.082	0.006	0.003	60.8
Max	-	-	-	1.49	0.69	0.34	0.26	0.31	0.008	0.492	0.333	0.119	0.024	0.011	91.3

612 Texture according to the FAO triangle (FAO, 1990), F: Fine, VF: Very Fine;  $D_b$ , bulk density;  $\text{CaCO}_3$ , calcium carbonate content;  $OC$ : organic carbon content;  $CEC$ , cation exchange capacity;  $SD$ ,  
613 standard deviation.  
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**Table 3.** Semi-quantitative evaluation of clay minerals identified by DRX.

Soil Sample	Clay minerals			
	Kaolinite	Illite	Smectite	Chlorite
JB 1-1	+	+	++	-
JB 2-1	+	+	+	-
JB 2-2	+	+	+	-
JB 2-3	+	+	+	-
SW 1-1	+	-	+++	+
SW 1-2	+	-	+++	+
TH 1-2	+	-	+++	+
TH 1-3	+	-	+++	+
QM 1-1	+	++	++	++
QM 1-2	+	++	++	++

618 +++ abundant, ++ moderately abundant, + not abundant, - not identified.

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622 **Table 4.** Water content at field conditions ( $W_{fc}$ ,  $\text{g g}^{-1}$ ) and at different water potentials ( $W_h$ ,  $\text{g g}^{-1}$ ).

Soil sample	$W_{fc}$	Water retained at a water potential of hPa ( $\text{g g}^{-1}$ )						
		$W_{-10}$	$W_{-33}$	$W_{-100}$	$W_{-330}$	$W_{-1000}$	$W_{-3300}$	$W_{-15000}$
JB 1-1	0.318	0.360	0.343	0.303	0.272	0.261	0.242	0.222
JB 2-1	0.262	0.331	0.301	0.284	0.254	0.241	0.236	0.207
JB 2-2	0.283	0.328	0.320	0.296	0.261	0.248	0.244	0.224
JB 2-3	0.292	0.342	0.330	0.317	0.265	0.251	0.245	0.224
SW 1-1	0.371	0.445	0.439	0.433	0.352	0.320	0.316	0.279
SW 1-2	0.375	0.447	0.424	0.408	0.340	0.338	0.322	0.279
TH 1-2	0.472	0.534	0.508	0.468	0.431	0.311	0.302	0.270
TH 1-3	0.507	0.540	0.532	0.483	0.451	0.423	0.414	0.385
QM 1-1	0.342	0.402	0.397	0.342	0.299	0.287	0.265	0.249
QM 1-2	0.344	0.382	0.357	0.341	0.302	0.290	0.264	0.255
Mean	0.357	0.411	0.395	0.368	0.323	0.297	0.285	0.259
SD	0.075	0.075	0.076	0.070	0.067	0.052	0.053	0.048
Min	0.262	0.328	0.301	0.284	0.254	0.241	0.236	0.207
Max	0.507	0.540	0.532	0.483	0.451	0.423	0.414	0.385

SD, standard deviation.

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**Table 5.** Characteristics calculated for the clay of the Syrian soils studied.

Soil Sample	$CEC_{cl}$ mmol <sub>+</sub> .g <sup>-1</sup>	$SSA_{cl}$ m <sup>2</sup> .g <sup>-1</sup>	$V_{p,cl}$ cm <sup>3</sup> .g <sup>-1</sup>
JB 1-1	0.707	153	0.695
JB 2-1	0.767	166	0.654
JB 2-2	0.815	172	0.690
JB 2-3	0.891	178	0.722
SW 1-1	0.762	143	0.718
SW 1-2	0.735	141	0.622
TH 1-2	0.720	113	0.613
TH 1-3	0.712	112	0.612
QM 1-1	0.745	115	0.718
QM 1-2	0.719	118	0.648
Mean	0.757	141	0.669
SD	0.054	24	0.042
Min	0.707	112	0.612
Max	0.891	178	0.722

630  $CEC_{cl}$ , cation exchange capacity of the clay;  $SSA_{cl}$ , specific surface  
631 area of the clay;  $V_{p,cl}$ , specific pore volume of the clay  
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**Table 6.** Regression equations between the water content of clay ( $W_{cl}$ ) at different water potentials and the clay fabric ( $V_{p,cl}$ ) calculated with the data published in tables 1, 2 and 3 by Bruand and Tessier (2000).

Water potential hPa	Regression equations calculated:					
	with the data published by Bruand and Tessier (2000) (n=37)			with both the data published by Bruand and Tessier (2000) and those recorded in this study (n=10)		
		R <sup>2</sup>	N		R <sup>2</sup>	N
-10	$W_{cl} = -0.0184 + 1.0516 V_{p,cl}$	0.96	37	$W_{cl} = -0.0107 + 1.0615 V_{p,cl}$	0.92	47
-33	$W_{cl} = -0.0150 + 1.0327 V_{p,cl}$	0.96	37	$W_{cl} = -0.0087 + 1.0378 V_{p,cl}$	0.93	47
-100	$W_{cl} = -0.0310 + 1.026 V_{p,cl}$	0.96	37	$W_{cl} = -0.0244 + 1.0201 V_{p,cl}$	0.94	47
-330	$W_{cl} = -0.0231 + 0.9779 V_{p,cl}$	0.96	37	$W_{cl} = -0.0135 + 0.9474 V_{p,cl}$	0.92	47
-1000	$W_{cl} = -0.0027 + 0.8865 V_{p,cl}$	0.96	37	$W_{cl} = +0.0030 + 0.8613 V_{p,cl}$	0.92	47
-3300	$W_{cl} = +0.0484 + 0.7387 V_{p,cl}$	0.95	37	$W_{cl} = +0.0531 + 0.7239 V_{p,cl}$	0.91	47
-15000	$W_{cl} = +0.1462 + 0.4269 V_{p,cl}$	0.84	37	$W_{cl} = +0.1479 + 0.4388 V_{p,cl}$	0.77	47

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650 **Table 7.** Mean error of prediction (*ME*), standard deviation (*SD*) and root mean square error (*RMSE*)  
651 recorded with the regression equations established between the gravimetric water content of clay ( $W_{cl}$ , in  
652  $g\ g^{-1}$  of oven dried clay) at different water potentials and the pore volume developed by the elementary  
653 clay particles ( $V_{p,cl}$ , in  $cm^3\ g^{-1}$  of oven dried clay) at field capacity.

Water potential hPa	<i>ME, SD and RSME</i> recorded with the regression equations established:								
	with the data published by Bruand and Tessier (2000) when applied to: (n=37)			with both the data published by Bruand and Tessier (2000) and those recorded in this study when applied to: (n=46)					
	the horizons of this study (n=10)			the horizons studied by Bruand and Tessier (2000) (n=37)			the horizons of this study (n=10)		
	<i>ME</i>	<i>SD</i>	<i>RMSE</i>	<i>ME</i>	<i>SD</i>	<i>RMSE</i>	<i>ME</i>	<i>SD</i>	<i>RMSE</i>
-10	-0.065	0.067	0.091	+0.014	0.043	0.045	-0.052	0.068	0.083
-33	-0.044	0.066	0.077	+0.010	0.040	0.040	-0.035	0.067	0.073
-100	-0.014	0.058	0.056	+0.002	0.040	0.039	-0.011	0.059	0.057
-330	+0.044	0.069	0.079	-0.011	0.041	0.042	+0.034	0.070	0.075
-1000	+0.047	0.050	0.067	-0.011	0.037	0.038	+0.037	0.051	0.061
-3300	+0.021	0.049	0.051	-0.005	0.035	0.035	+0.017	0.050	0.050
-15000	-0.043	0.042	0.058	+0.011	0.040	0.041	-0.034	0.043	0.053
Mean	-0.008	0.057	0.068	0.001	0.039	0.040	-0.006	0.058	0.065
Min	-0.065	0.042	0.051	-0.011	0.035	0.035	-0.052	0.043	0.050
Max	+0.047	0.069	0.091	+0.014	0.043	0.045	+0.037	0.070	0.083

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**Table 8.** Mean error of prediction (*ME*), standard deviation (*SD*) and root mean square error (*RMSE*) recorded with the regression equations established between the volumetric water content of clay ( $\theta_v$ , in  $\text{cm}^3 \text{cm}^{-3}$ ) at different water potentials *h* and both the clay content and the reciprocal of bulk density measured in conditions close to field capacity with both the data published by Bruand and Tessier (2000) and those recorded in this study when applied to the horizons of this study.

Water potential (hPa)	n=10		
	<i>ME</i> ( $\text{cm}^3/\text{cm}^3$ )	<i>SD</i> ( $\text{cm}^3/\text{cm}^3$ )	<i>RMSE</i> ( $\text{cm}^3/\text{cm}^3$ )
-10	-0.024	0.054	0.054
-33	-0.028	0.054	0.059
-100	-0.011	0.046	0.045
-330	+0.021	0.053	0.054
-1000	+0.025	0.039	0.044
-3300	+0.010	0.039	0.039
-15000	-0.025	0.036	0.042
Mean	-0.005	0.046	0.048
Min	-0.028	0.036	0.039
Max	+0.025	0.054	0.059

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