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WATER RETENTION AND AVAILABILITY IN SOILS OF THE STATE OF SANTA CATARINA-BRAZIL: EFFECT OF TEXTURAL CLASSES, SOIL CLASSES AND LITHOLOGY[1]

André da Costa[2], Jackson Adriano Albuquerque[3], Adriano da Costa[4], Patricia Pértile[5] & Franciani Rodrigues da Silva[6]

SUMMARY

The retention and availability of water in the soil vary according to the soil characteristics and determine plant growth. Thus, the aim of this study was to evaluate water retention and availability in the soils of the State of Santa Catarina, Brazil, according to the textural class, soil class and lithology. The surface and subsurface horizons of 44 profiles were sampled in different regions of the State and different cover crops to determine field capacity, permanent wilting point, available water content, particle size, and organic matter content. Water retention and availability between the horizons were compared in a mixed model, considering the textural classes, the soil classes and lithology as fixed factors and profiles as random factors. It may be concluded that water retention is greater in silty or clayey soils and that the organic matter content is higher, especially in Humic Cambisols, Nitisols and Ferralsol developed from igneous or sedimentary rocks. Water availability is greater in loam-textured soils, with high organic matter content, especially in soils of humic character. It is lower in the sandy texture class, especially in Arenosols formed from recent alluvial deposits or in gravelly soils derived from granite. The greater water availability in the surface horizons, with more organic matter than in the subsurface layers, illustrates the importance of organic matter for water retention and availability.

Index terms: field capacity, permanent wilting point, available water capacity, particle size, mixed models.

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RESUMO: *RETENÇÃO E DISPONIBILIDADE DE ÁGUA EM SOLOS DE SANTA CATARINA: EFEITO DAS CLASSES TEXTURAIS, CLASSES DE SOLO E LITOLOGIAS*

A retenção e a disponibilidade de água variam com os atributos do solo e determinam o crescimento das plantas. Nesse sentido, este estudo objetivou avaliar a retenção e a disponibilidade de água nos solos de Santa Catarina, em razão da classe textural, classe de solo e litologia. Foram amostrados os horizontes superficiais e subsuperficiais de 44 perfis de solo, em áreas de diferentes regiões do Estado e coberturas vegetais, para a determinação da capacidade de campo, ponto de murcha permanente, água disponível, granulometria e teor de matéria orgânica. A retenção e a disponibilidade de água foram comparadas entre os horizontes por meio de um modelo misto, considerando as classes texturais, classes de solo e litologias, como fatores fixos, e os perfis, como fatores aleatórios. A retenção de água foi maior em solos argilosos ou siltosos e com maior teor de matéria orgânica, especialmente nos Cambissolos Húmicos, Nitossolos e Latossolos desenvolvidos de rochas ígneas afaníticas ou sedimentares, como folhelhos, argilitos e siltitos. A disponibilidade de água foi maior em solos de textura franca, com elevados teores de matéria orgânica, principalmente nos com caráter húmico; e menor em solos da classe textural areia, principalmente nos Neossolos Quartzarênicos, formados a partir de depósitos aluvionares recentes ou em solos cascalhentos, derivados de granito. A maior disponibilidade de água nos horizontes superficiais, com mais matéria orgânica, em comparação aos subsuperficiais, comprovou a importância da matéria orgânica na retenção e disponibilidade de água.

Termos de indexação: capacidade de campo, ponto de murcha permanente, água disponível, granulometria, modelos mistos.

INTRODUCTION

Simulation models that evaluate water movement in the soil-plant-atmosphere system are an important tool in agriculture and in environmental management. Nevertheless, the use of these models is limited due to the need for a large number of soil properties as input variables, such as water retention and availability in the soil for plants (Wösten et al., 1999), and these properties are strongly affected by soil texture, mineralogy, organic matter content and management (Hillel, 1998).

Generally soils with finer particle sizes retain more water; nevertheless, as moisture increases in both field capacity (FC) and in the permanent wilting point (PWP), this does not always result in greater available water content (Rawls et al., 1982; Gaiser et al., 2000; Al Majou et al., 2008; Reichert et al., 2009). Furthermore, it is important to consider that there are confounding factors in the relation between texture and water retention in the soil. This occurs because in more clayey soils, the chemical and physical protection of organic matter is generally greater (Oades, 1988; Dieckow et al., 2009), especially in soils of colder and wetter regions (Tate, 1992; Chen & Chiu, 2000; Dalmolin et al., 2006). This condition raises the organic matter content and, consequently, water retention, especially at low tensions (Rawls et al., 2003). Another soil property that affects water retention and availability is mineralogy. In soils with predominance of 2:1 clay minerals water retention and availability are higher than in kaolinitic soils (Gaiser et al., 2000).

Since the soil particle size, mineralogical composition and organic matter content are rather variable according to the lithology, altitude and climate, studies must adress the relation of water retention and availability to the other soil properties for each location of interest. In such studies, one tries to group the different profiles according to other soil properties. Generally, use is made of the soil textural class (Rawls et al, 1982; Al Majou et al., 2008), the soil class using different taxonomic systems (Batjes, 1996) or soil lithology (Bastet, 1999) as a criterion for grouping the soil profiles or horizons. In developed countries, the relation between soil properties and water retention and/or availability is evaluated using large databases, such as the NRCS (Soil Survey Staff, 1995) and the HYPRES (Wösten et al., 1999), while in the other countries these studies are generally lacking, which impedes the use of simulation models (Hodnett & Tomasella, 2002).

In the soils of Santa Catarina, few studies have been carried out to determine soil water retention and availability for plants (Veiga et al., 2008; Costa et al., 2009; Morales et al., 2010). As the lithology, relief and climate of the soils of this state are highely variable, various soil classes were formed (containing from sandy textured to very clayey textured soils) (Embrapa, 2004). Thus, in more clayey soils, such as Latossolos (Ferralsols) and Nitossolos (Nitisols) derived from extrusive igneous rocks, the moisture content at field capacity and the permanent wilting point should be higher, raising the available water content for plants in comparison to sandy soils derived from alluvial sediments. In addition, the differentiated climate of Santa Catarina, which is constantly moist, associated with high altitudes in some regions of the State, results in a climate ranging from humid subtropical to temperate, favoring the predominance of 1:1 clay minerals (kaolinite) and a greater accumulation of organic matter in the soil, mainly in more clayey highland soils, in comparison to soils of the same lithology and textural class as in other states of Brazil. The predominance of kaolinite may result in low available water contents in the soils of Santa Catarina, which may be attenuated by the effect of the high contents of organic matter in the surface horizons.

Nevertheless, so far, these hypotheses cannot be confirmed by the quantity of information available on soils of the State of Santa Catarina. Thus, the purpose of this study was to evaluate and compare water retention and availability in soils of different textural classes, soil classes and lithologies located in the state of Santa Catarina, in the southern region of Brazil.

MATERIALS AND METHODS

The study analyzed 44 profiles, representing the main soil classes of the State of Santa Catarina, consisting of two Argissolos Amarelos (Acrisols), two Argissolos Vermelhos (Acrisols), five Argissolos Vermelho-Amarelos (Acrisols), two Cambissolos Háplicos (Cambisols), four Cambissolos Húmicos (Cambisols), two Chernossolos Argilúvicos (Chernozems), one Chernossolo Háplico (Chernozem), one Latossolo Amarelo (Ferralsol), one Latossolo Bruno (Ferralsol), three Latossolos Vermelhos (Ferralsols), one Latossolo Vermelho-Amarelo (Ferralsol), four Neossolos Litólicos (Leptosols), three Neossolos Quartzarênicos (Arenosols), nine Nitossolos Brunos (Nitisols) and four Nitossolos Vermelhos (Nitisols). The choice of the profiles was based on the availability of survey data of soils of Santa Catarina with the morphological and mineralogical description of the soil in modal profiles. The climate in the State is Cfa or Cfb, according to the Köppen classification (Epagri/Ciram, 2002).

Lithology was determined for each soil based on the rocks found in the profile, considering the geological map and the lithostratigraphic column of the State of Santa Catarina, as presented by Zanini et al. (1997). The horizons A, AB, BA and B, when present, and their subdivisions (A1, A2, B1 and B2) were studied in each profile, and horizons A and C of Neossolos Quartzarênicos (Arenosols). In the middle part of each horizon, undisturbed samples were collected with stainless steel cylinders (diameter 6.0 cm, height 2.5) pushed into the soil, in quadruplicate, as well as composite disturbed samples.

The undisturbed samples were saturated by capillarity and stabilized at water tensions of 1, 6 and 10 kPa in a sand suction column (Reinert & Reichert, 2006) and at tensions of 33, 100, 300, 500 and 1,500 kPa in Richards' chambers (Richards, 1949). Field capacity (FC) was considered as the volumetric soil moisture at a tension of 10 kPa (pore diameter = 30 μm); permanent wilting point (PWP) as the volumetric moisture at 1,500 kPa (pore diameter = 0.2 μm); and the available water content (AW) as the volume of water retained between 10 and 1,500 kPa.

The following properties were determined in the disturbed samples: soil particle size by the pipette method according to Day (1965), to classify the soil according to the textural classes (Santos et al., 2005); and organic matter (OM) content by multiplication with the factor 1.724 of the total organic carbon content determined by the Walkley-Black method modified by Tedesco et al. (1995).

Statistical analysis was carried out after the creation of two soil groups because the surface horizons differed from the subsurface horizons in OM content. The database was thus divided into two groups: horizons O, A, AB, AC and their subdivisions were grouped as "surface" horizons, and horizons BA, B, C and their subdivisions were grouped as "subsurface" horizons. The grouping of horizons by their position in the profile generally reduces the standard error in the estimation of water retention and availability in the soil (Bruand, 2004a).

The effects of the textural class (13 classes), of the soil class at the suborder level (according to Embrapa, 2006) and of the lithology with regard to FC, PWP and AW were analyzed for each group of horizons. For this purpose, univariate statistical analysis was used in a mixed model with the "PROC GLIMMIX" procedure of the SAS 9.2 program (Schabenberger, 2007). In this analysis, the soil class, the textural class or the lithology were considered as a fixed effect and the profiles as a random effect. Due to the different number of horizons in each soil profile, which were separated into "surface" and "subsurface" horizons, the effect of the order of position of each horizon in the soil profile was included using the "random residual" option in the statistical model. For example, all B1 horizons (including Bt1, Bw1, Bi, and Bt) were denominated by a single name.

The mean values of FC, PWP and AW in each textural class, soil class or lithology were compared by the least significant difference (LSD) test. Due to the use of a mixed statistical model, similar mean values may have different letters. This occurs because the comparison method calculates a standard error for the mean value of each one of the levels of fixed effect. Consequently, a level with greater variability in its replications will be statistically similar to a greater number of levels.

RESULTS AND DISCUSSION

Water retention and availability in the soil *versus* textural classes

In the surface horizons, the field capacity (FC) and permanent wilting point (PWP) were similar for most textural classes. This was the result of the large variability in FC and PWP observed within a single textural class, which raised the standard error of the estimate. Consequently, soils had mean values with differences of up to 0.14 $cm^3 cm^{-3}$ for FC and 0.10 $cm^3 cm^{-3}$ for PWP that were considered statistically similar (Table 1). In the subsurface horizons, the variability among soils with a similar textural class was lower, resulting in a clearer distinction among textural classes by soil water retention (Table 1). The greater variability in water retention in the surface horizons occurred by the more intense weathering effect through the activity of microorganisms, of plants, of wetting and drying cycles, and also of the anthropic effect through soil use and management. The combination of these effects resulted in a high standard error of the estimate of OM contents in surface horizons of soils of the same textural class. This variability of the OM contents, associated with the different uses of the soils of Santa Catarina, results in changes in soil structure, which alters the distribution of pores, water adsorption and water retention in the soil at lower suctions (Braida et al., 2011). In contrast, alteration in the OM contents in soils with the same particle sizes also modifies the water retention capacity at high suctions due to alteration in the specific surface area of the soil and in the quantity of water adsorbed by chemical bonds (Resurreccion et al., 2011). In addition to the OM contents, as the soils of Santa Catarina are derived from distinct materials of origin (Embrapa, 2004) which underwent different pedogenetic processes, the high standard error of PWP in soils of similar particle size may also be related to the variations in the mineralogy of the soils evaluated due to its effect on the specific surface area of the soil and on water retention (Bruand, 2004b).

In the surface horizons, FC was greater (0.41-0.55 $cm^3 cm^{-3}$) in soils with predominance of particles with diameter less than 0.53 μm, including the clayey and loamy soils and their variations (Table 1). The FC values (0.26 $cm^3 cm^{-3}$) were intermediate in the sandy loam soils, and lowest (0.16 $cm^3 cm^{-3}$) in soils of the sandy class. The PWP was also greater in the clayey and/or silty soils and lower in the sandy soils. In the

Table 1. Soil moisture at field capacity (FC), permanent wilting point (PWP) and available water content (AW) in horizons grouped according to the soil textural classes of the State of Santa Catarina

Textural class	FC		PWP		AW	
	Mean	SE(1)	Mean	SE	Mean	SE
	$cm^3 cm^{-3}$					
			Surface horizon			
Silty clay loam	0.55 a	0.08	0.38 ab	0.06	0.17 abc	0.03
Clay	0.52 a	0.03	0.39 a	0.02	0.13 abcd	0.01
Silty clay	0.51 a	0.03	0.36 ab	0.03	0.15 ab	0.01
Very clayey	0.48 a	0.02	0.36 ab	0.02	0.11 cd	0.01
Loam	0.46 a	0.04	0.30 b	0.03	0.16 a	0.01
Clayey loam	0.46 a	0.03	0.31 b	0.02	0.15 ab	0.01
Sandy clay loam	0.41 ab	0.06	0.31 ab	0.05	0.10 bcd	0.02
Silty loam	0.41 a	0.05	0.28 b	0.04	0.14 abcd	0.02
Sandy loam	0.26 bc	0.04	0.15 c	0.03	0.12 bcd	0.02
Sand	0.16 c	0.05	0.07 c	0.04	0.09 d	0.02
			Subsurface horizon			
Silty clay	0.56 a	0.06	0.43 a	0.05	0.13 a	0.02
Very clayey	0.52 a	0.01	0.43 a	0.01	0.09 b	0.01
Clay	0.50 ab	0.01	0.41 a	0.01	0.10 ab	0.00
Clayey loam	0.42 c	0.02	0.31 b	0.02	0.11 ab	0.01
Sandy clay loam	0.41 c	0.03	0.31 b	0.03	0.11 ab	0.01
Loam	0.39 bcd	0.06	0.26 bc	0.05	0.13 ab	0.02
Sandy loam	0.24 de	0.04	0.15 cd	0.04	0.09 ab	0.01
Loamy sand	0.22 de	0.06	0.10 d	0.05	0.12 ab	0.02
Sand	0.19 e	0.03	0.09 d	0.03	0.10 ab	0.01

(1) SE: standard error. Lower case letters compare the classes in each horizon by the LSD test ($F<0.05$).

subsurface horizons, moisture values in FC and PWP were higher in horizons with silty clay texture, very clayey texture and clayey texture soils (Table 1), all with high clay, silt and OM contents (Table 2). Intermediate values of FC and PWP occurred in horizons with clayey loam, sandy clay loam and loam texture, which are characterized by a balanced distribution of the particle size fractions (about one third each of clay, silt and sand). Lower FC and PWP occurred in soils with sandy loam, loamy sand and sandy texture.

The increase in FC and PWP in soils with higher clay and silt contents was also observed in Rio Grande do Sul, RS (Reichert et al., 2009), the USA (Rawls et al., 1982), France (Al Majou et al., 2008), and in soils of a semiarid tropical climate in the northeastern region of Brazil and in the Southeast of Nigeria (Gaiser et al., 2000). Lower water retention in the sandier soils occurs due to the predominance of large diameter pores (>30 μm), which are drained at low suctions, while in soils with a more clayey texture, smaller-diameter pores predominate (<0.2 mm), which favor the increase of water retention <30 μm high suctions and water availability in the soil (Petersen et al., 1968). The variations in water retention and availability in soils of Santa Catarina were also similar to those of the theoretical model developed by Buckman & Brady (1964).

Greater FC and PWP were observed for most textural classes of the soils of Santa Catarina (SC) in comparison to soils of RS, the USA, France and other regions of a semiarid tropical climate. The cause of the greater water retention may be associated with the high OM content observed in the soils of Santa Catarina, promoting the increase in water retention, regardless of the soil texture (Rawls et al., 2003). The mean OM content of the soils of Santa Catarina was 47 g kg^{-1} in the surface horizons and 17 g kg^{-1} in the subsurface horizons (mean of 30 g kg^{-1}), which is greater than the mean contents of the databases used by Reichert et al. (2009), Rawls et al. (1982), Al Majou et al. (2008) and Gaiser et al. (2000). The greater OM content of the soils of SC is a consequence of the climatic conditions and of lithology. The accumulation of OM in the soil is favored in regions with a cold and wet climate (Tate, 1992; Chen & Chiu, 2000; Dalmolin et al., 2006) and in soils with a predominance of clay (Almeida et al., 1997, 2003; Corrêa, 2003; Embrapa, 2004). These factors reduce microbial activity and protect the organic matter chemically and physically

Table 2. Number of horizons (n), mean contents and standard error (SE) of the estimate for clay, silt, sand and organic matter (OM) in horizons grouped according to the textural classes of the soils of the State of Santa Catarina

Textural class		Clay		Silt		Sand		OM	
	n	Content	SE	Content	SE	Content	SE	Content	Se
		g kg^{-1}							
		Surface horizon							
Very clayey	30	682	13	257	17	62	18	43	12
Clay	13	491	16	303	21	206	21	53	14
Silty clay	6	430	19	448	25	122	26	69	17
Silty clay loam	2	389	47	570	62	40	64	100	41
Clayey loam	11	324	16	376	21	300	21	66	14
Sandy clay loam	2	285	34	213	44	501	45	38	29
Silty loam	5	228	27	535	36	237	37	48	24
Loam	7	220	21	374	28	405	29	74	19
Sandy loam	9	147	24	106	31	747	32	16	21
Sand	5	37	27	20	36	943	37	12	24
		Subsurface horizon							
Very clayey	58	695	11	207	12	98	14	19	2
Clay	26	523	14	279	15	198	18	17	2
Silty clay	1	435	57	516	61	49	73	40	7
Clayey loam	8	341	23	306	25	353	30	16	2
Sandy clay loam	7	294	28	174	30	532	36	17	3
Loam	1	267	57	494	61	239	73	21	7
Sandy loam	2	174	40	116	43	711	52	14	5
Loamy sand	1	85	5	28	61	887	73	5	7
Sand	6	35	33	26	35	939	42	7	3

by their interaction with soil clay minerals (Oades, 1988; Dieckow et al., 2009).

In the soils of SC, the OM contents had a positive linear relationship to the clay+silt contents for the surface and subsurface horizons (Figure 1a, b), with a greater angular coefficient in the surface horizons, confirming the interaction observed by Oades (1988) and Dieckow et al. (2009). This interaction results in an additive effect of the fine soil particles with the OM in the sense of increasing the available water content (AW) since the AW varied little among the textural classes in the subsurface horizons (Figure 2).

In regard to AW content, greater amplitude was observed in the surface horizons (0.08 cm^3 cm^{-3}) in relation to the subsurface horizons (0.04 cm^3 cm^{-3}) (Figure 2). In the surface horizons, AW is greater in soils with greater silt as well as OM contents (Table 2), including soils of silty clay loam, loam, clayey loam and silty clay texture, with variation from 0.15 to 0.17 cm^3 cm^{-3} (Table 1). Intermediate contents of AW occurred in the clayey, very clayey, sandy loam and sandy clay loam classes (variation 0.10-0.13 cm^3 cm^{-3}). Lower AW contents occurred in soils with a sandy texture, with a mean value of 0.09 cm^3 cm^{-3}. In percentage, the surface horizons of the soils with silty clay loam, loam, clayey loam and silty clay textures have a 44 and 78 % greater AW content than the very clayey and sandy-textured soils, respectively.

In the subsurface horizons, although water retention is greater in clayey texture soils (Figure 2b), the AW content of most textural classes was similar (0.09-0.13 cm^3 cm^{-3}), differing only among the horizons with silty clay and very clayey texture (Table 1). The greater water availability observed in the surface horizons in loamy to clayey soils in comparison to that observed in the subsurface horizons is due to greater OM content (Braida et al., 2011) and to the soil structure in the surface horizons.

Thus, among the main textural classes evaluated, highest water contents are available to plants in soils with loamy texture and high silt and clay levels, as similarly observed in the south of Brazil, the USA and France (Rawls et al, 1982; Al Majou et al., 2008; Reichert et al., 2009). In the subsurface horizons of the soils of SC, the textural class has little influence on water availability.

A similarity was observed in the AW content in most textural classes of the soils of SC and RS (Reichert et al., 2009) and of the region near Paris, France (Al Majou et al., 2008), mainly in the soil surface horizons. This may be atrributed to the clay type in the soil, since the climate types Cfa and Cfb are somewhat similar (Köppen & Geiger, 1928), which favors the formation of 1:1 type clay minerals and, to a lesser extent, 2:1 type clay minerals. Nevertheless, the soils of the USA have greater AW content in most textural classes, compared to the soils of SC. This difference is probably due the predominance of soils with high activity clay of the 2:1 type (Nettleton et al., 1983; Rawls et al., 2003), while in SC soils with kaolinite, 2:1 type clay minerals with hydroxy-aluminum interlayers and iron oxides predominate (Almeida et al., 1997, 2003; Corrêa, 2003; Paes Sobrinho et al., 2009; Bringhenti, 2010). The increase in water availability provided by the 2:1 type clay minerals has not been studied in detail (Bruand, 2004b); nevertheless, the studies of Gaiser et al. (2000) and Reichert et al. (2009) indicate a positive relation between these soil properties.

Water retention and availability *versus* soil classes

The grouping of the profiles according to the soil classes of the Brazilian Soil Classification System (Sistema Brasileiro de Classificação de Solos - SiBCS) (Embrapa, 2006) at the level of suborders indicated differences in water retention, mainly in the surface horizons (Table 3). Nevertheless, FC and PWP in

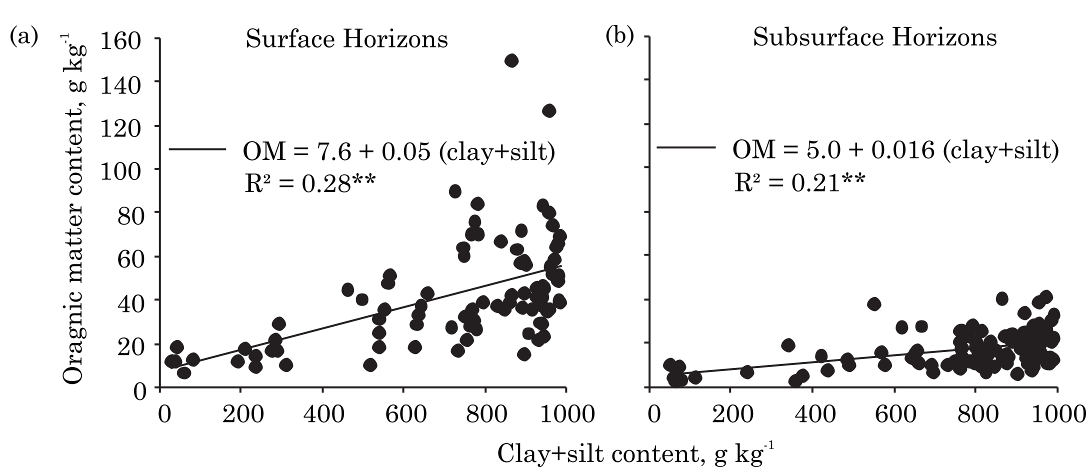

Figure 1. Relation between organic matter (OM) contents with the clay+silt contents for the surface (a) and subsurface (b) horizons of the soils of the State of Santa Catarina. ** model significant at 1 %.

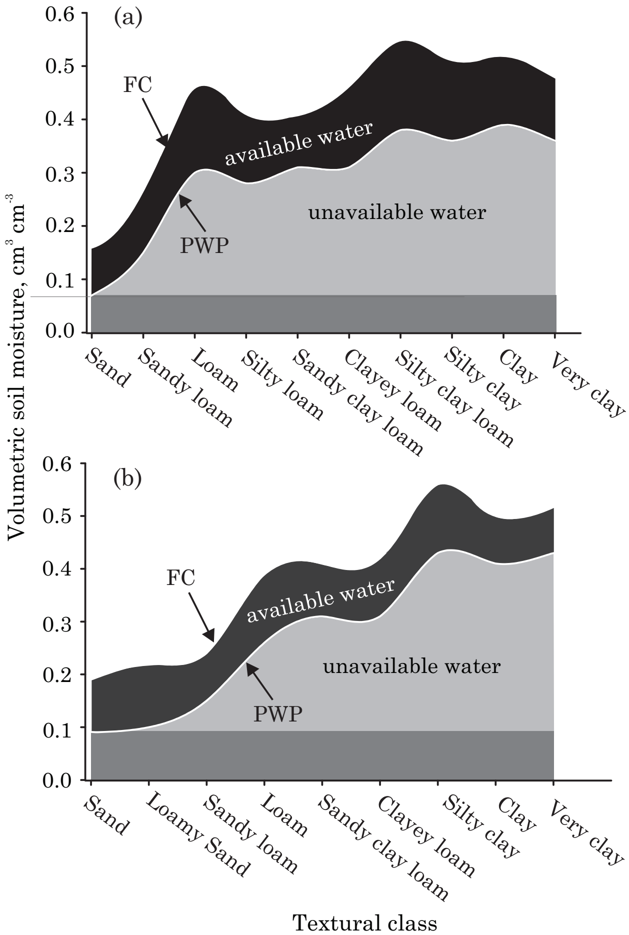

Figure 2. Variation of field capacity (FC), permanent wilting point (PWP) and available water content (AW) according to the textural class of surface (a) and subsurface (b) horizons of the soils of the State of Santa Catarina.

the surface horizon were statistically equal among soils, with differences in the mean values of up to 0.15 cm^3 cm^{-3}, indicating great variability in water retention among soils of the same class at the suborder level.

In the surface horizons, FC and PWP had greater contents in the Cambissolos (Cambisols) (especially in the Cambissolos Húmicos), Nitossolos (Nitisols) and Latossolos (Ferralsols); intermediate contents in the Argissolos (Acrisols), Neossolos Litólicos (Leptosols) and Chernossolos (Chernozems); and lower contents in the Neossolos Quartzarênicos (Arenosols) (Table 3). In the subsurface horizons, FC and PWP were similar for most soil classes, with the exception of the Neossolos Quartzarênicos (Arenosols), which had lower water retention (Table 3).

Greater water retention in the surface horizons of the Cambissolos Húmicos (Humic Cambisols) is associated with their clayey loam texture and greater OM content, which is greater in this soil class than in the other classes evaluated (18 to 47 g kg^{-1}) (Table 4). The high FC and PWP of the Latossolos (Ferralsols) and Nitossolos (Nitisols) are also associated with the high clay and OM contents. Lower water retention in the Neossolos Quartzarênicos (Arenosols) (Table 3), however, is due to their high sand content (more than 900 g kg^{-1}) (Table 4), resulting in the predominance of macropores.

The AW content in the surface horizons of the soils of SC differed up to 0.10 cm^3 cm^{-3} (Table 3) among the suborders. It was highest in the Cambissolos Húmicos (Humic Cambisols) and Neossolos Litólicos (Leptosols) (0.16-0.19 cm^3 cm^{-3}) and lowest in the other classes, which did not differ from each other (0.09-0.14 cm^3 cm^{-3}). In the subsurface horizons, the AW differed among few soil classes since the amplitude of AW was only 0.05 cm^3 cm^{-3}. Among the classes, the Cambissolos Húmicos (Humic Cambisols) had greater AW contents, and the Nitossolos Brunos (Nitisols) had lower contents. In regard to the other classes, AW had intermediate contents, not differing from each other (Table 3). The greater water availability in the surface horizons of the Cambissolos Húmicos (Humic Cambisols) and Neossolos Litólicos (Leptosols) occurred due to the additive effect of two properties, greater OM contents, and clay, silt and sand contents near the 1/3 ratio of each fraction. At this proportion, the macropores formed by the sand fraction may be occupied by the silt and clay fractions, forming intermediate diameter pores, responsible for the retention of the available water.

Batjes (1996) evaluated the AW content (33-1,500 kPa) of soils that form the "World Inventory of Soil Emission Potentials (WISE)" database, consisting of 4,352 profiles and used to create the Soil Map of the World of the FAO-Unesco. Similalry as in the soils of SC, Batjes (1996) observed greater AW in the Humic Cambisols (FAO, 1991), which correspond approximately to the order of the Cambissolos Húmicos in the SiBCS (Embrapa, 2006). In relation to the classes of Argissolos, Latossolos and Nitossolos of the SiBCS (Embrapa, 2006), which correspond approximately to the classes of Acrisols, Ferralsols and Nitisols, respectively, by the FAO (1991) classification, the AW was approximately 0.04 cm^3 cm^{-3} greater in the Acrisols (mean of 0.12 cm^3 cm^{-3}) in comparison to the Ferralsols and Nitosols (mean of 0.08 cm^3 cm^{-3}), i.e., a difference of 50 % in the AW content (Batjes, 1996). Batjes (1996) attributed the effect of soil mineralogy as a cause of lower water availability in the Ferralsols and Nitisols, since 1:1 type clay minerals and oxides predominate in these soils, while 2:1 type clay minerals predominate in the Cambisols and Acrisols. In the soils of SC, this difference was not observed, since the AW contents of these three soil classes was medium 0.12 cm^3 cm^{-3} in the surface horizons and 0.10 cm^3 cm^{-3} in the subsurface horizons.

Another difference observed was in regard to the class of the Neossolos Quartzarênicos (Arenosols), which had AW contents in the surface and subsurface horizons similar to other classes, such as in the Latossolos (Ferralsols), Nitossolos (Nitisols), Chernossolos (Chernozems) and Argissolos (Acrisols). In contrast, Batjes (1996) observed that the soils corresponding to this class, called Arenosols in the FAO (1991) classification, have AW contents of around 50 % (AW = 0.04 $cm^3 cm^{-3}$) of those in the Neossolos Quartzarênicos Arenosols of SC. This greater water availability in the sandy soils of Santa Catarina may be mainly related to the fine sand contents of these soils, which ranged from 681 to 783 g kg^{-1} (Table 4), and have a positive relation to water availability (Costa, 2012).

Water retention and availability *versus* soil lithology

The physical properties related to water retention also differed according to the soil lithology (Table 5). In the surface horizons, greater FC and PWP occurred in the soils derived from extrusive igneous rocks from the Serra Geral Formation (basaltic andesite, basalt, amygdaloidal basalt, dacite, rhyodacite), which give rise to soils with clayey or very clayey textural classes (Embrapa, 2006) and with mean OM contents (above 50 g kg^{-1}) (Table 6); intrusive igneous (hornblendite, except for granite), metamorphic rocks (muscovite garnet schist, mafic

Table 3. Soil moisture at field capacity (FC), permanent wilting point (PWP), and available water content (AW), in different soil classes in the State of Santa Catarina

Soil class(1) - suborder	FC		PWP		AW	
	Mean	SE(2)	Mean	SE	Mean	SE
	$cm^3 cm^{-3}$					
	Surface horizon					
Cambissolo Húmico (Cambisol)	0.55 a	0.04	0.37 ab	0.04	0.19 a	0.01
Nitossolo Bruno (Nitisol)	0.50 ab	0.03	0.39 a	0.02	0.12 cd	0.01
Latossolo Bruno (Ferralsol)	0.49 abc	0.09	0.36 abc	0.07	0.13 abcd	0.03
Nitossolo Vermelho (Nitisol)	0.47 abc	0.03	0.35 abc	0.04	0.12 bcd	0.01
Latossolo Vermelho Amarelo (Ferralsol)	0.44 abc	0.09	0.30 abc	0.07	0.14 abcd	0.03
Cambissolo Háplico (Cambisol)	0.43 abc	0.06	0.31 abc	0.05	0.12 bcd	0.02
Latossolo Vermelho (Ferralsol)	0.43 abc	0.05	0.31 abc	0.04	0.12 bcd	0.02
Argissolo Amarelo (Acrisol)	0.42 abc	0.05	0.29 abc	0.04	0.14 bc	0.02
Latossolo Amarelo (Ferralsol)	0.40 abc	0.09	0.27 abc	0.07	0.12 bcd	0.03
Neossolo Litólico (Leptosol)	0.40 bc	0.04	0.24 c	0.04	0.16 ab	0.01
Chernossolo Argilúvico (Chernozem)	0.39 bc	0.06	0.27 bc	0.05	0.13 bcd	0.02
Argissolo Vermelho Amarelo (Acrisol)	0.38 c	0.04	0.27 bc	0.03	0.11 cd	0.01
Chernossolo Háplico (Chernozem)	0.38 abc	0.09	0.25 abc	0.07	0.13 abcd	0.03
Argissolo Vermelho (Acrisol)	0.35 bcd	0.09	0.21 bcd	0.07	0.14 abcd	0.03
Neossolo Quartzarênico (Arenosol)	0.16 d	0.05	0.07 d	0.04	0.09 d	0.02
	Subsurface horizon					
Chernossolo Háplico (Chernozem)	0.55 ab	0.07	0.46 ab	0.07	0.09 abc	0.02
Nitossolo Bruno (Nitisol)	0.53 a	0.02	0.45 a	0.02	0.08 c	0.01
Cambissolo Húmico (Cambisol)	0.52 ab	0.03	0.39 ab	0.03	0.13 a	0.01
Nitossolo Vermelho (Nitisol)	0.52 ab	0.02	0.43 ab	0.03	0.10 bc	0.01
Argissolo Amarelo (Acrisol)	0.51 ab	0.04	0.41 ab	0.04	0.10 abc	0.01
Latossolo Vermelho (Ferralsol)	0.50 ab	0.04	0.39 ab	0.04	0.11 ab	0.01
Argissolo Vermelho (Acrisol)	0.48 ab	0.07	0.39 ab	0.07	0.09 abc	0.02
Chernossolo Argilúvico (Chernozem)	0.48 ab	0.05	0.38 ab	0.05	0.10 abc	0.01
Latossolo Bruno (Ferralsol)	0.48 ab	0.07	0.39 ab	0.07	0.09 abc	0.02
Latossolo Amarelo (Ferralsol)	0.46 ab	0.07	0.37 ab	0.07	0.09 abc	0.02
Cambissolo Háplico (Cambisol)	0.45 ab	0.05	0.36 ab	0.05	0.09 abc	0.01
Argissolo Vermelho Amarelo (Acrisol)	0.44 b	0.03	0.34 b	0.03	0.10 bc	0.01
Latossolo Vermelho Amarelo (Ferralsol)	0.41 abc	0.07	0.31 abc	0.07	0.10 abc	0.02
Neossolo Litólico (Leptosol)	0.24 cd	0.07	0.14 cd	0.07	0.09 abc	0.02
Neossolo Quartzarênico (Arenosol)	0.20 d	0.04	0.10 d	0.04	0.10 abc	0.01

(1) Embrapa (2006); (2) SE: standard error. Lower case letters compare the soil classes in each horizon by the LSD test (F<0.05).

granulite, migmatite, parametamorphic); and fine texture sedimentary rocks (Shales or siltstones), which gave rise to medium texture soils (Embrapa, 2006) and medium OM contents (35 to 50 g kg^{-1}) (Table 5). Soils with intermediate FC and PWP moisture contents were those derived from sedimentary rocks, which gave rise to soils with loam texture (Embrapa, 2006), but with clay contents of approximately 170 g kg^{-1} and with medium OM contents (approximately 35 g kg^{-1}). The moisture contents of FC and PWP were lowest in soils derived from rocks or quartz-rich sedimentary deposits (Botucatu sandstone and recent alluvial deposits), which gave rise to soils with a sandy texture (Embrapa, 2006) and medium OM contents (20 to 25 g kg^{-1}); and also in the soils derived from granite, which gives rise to soils with sandy texture with medium OM contents (35 g kg^{-1}), differing from the other soils in the high gravel (186 g kg^{-1}) and coarse sand (356 g kg^{-1}) contents (Table 5).

In the subsurface horizons, the decreasing order of FC and PWP according to the soil lithology was very similar to that observed in the surface horizons (Table 5), while the OM content was lower and clay content higher (Table 6). Nevertheless, the rate of OM reduction and of the increase in clay content according to soil depth varied among the soils of different lithologies.

Table 4. Number of horizons (n), mean values and standard error (SE) of the estimate for clay, silt, sand and organic matter (OM) contents in soils grouped by soil classes in the State of Santa Catarina

Textural class	n	Clay		Silt		Sand		OM	
		Content	SE	Content	SE	Content	SE	Content	Se
		g kg^{-1}							
		Surface horizon							
Latossolo Vermelho (Ferralsol)	8	744	50	207	59	49	87	41	19
Latossolo Bruno (Ferralsol)	3	692	87	254	101	54	150	55	33
Nitossolo Bruno (Nitisol)	24	620	29	301	34	80	50	50	10
Nitossolo Vermelho (Nitisol)	7	472	44	369	51	159	75	47	16
Cambissolo Háplico (Cambisol)	3	441	62	390	72	167	106	29	22
Latossolo Amarelo (Ferralsol)	2	409	88	227	102	364	150	33	33
Cambissolo Húmico (Cambisol)	9	369	44	392	51	239	75	93	16
Latossolo Vermelho Amarelo (Ferralsol)	2	335	88	261	102	405	150	34	33
Chernossolo Háplico (Chernozem)	2	280	88	485	102	235	150	33	33
Argissolo Vermelho Amarelo (Acrisol)	9	264	39	201	46	533	67	36	14
Chernossolo Argilúvico (Chernozem)	4	252	62	500	72	248	106	48	22
Neossolo Litólico (Leptosol)	6	238	44	276	51	483	75	62	16
Argissolo Amarelo (Acrisol)	3	230	51	378	59	392	87	53	19
Argissolo Vermelho (Acrisol)	3	171	87	359	101	470	150	19	33
Neossolo Quartzarênico (Arenosol)	5	36	51	20	59	943	87	12	19
		Subsurface horizon							
Latossolo Vermelho (Ferralsol)	9	792	63	168	36	40	59	19	3
Nitossolo Bruno (Nitisol)	27	702	37	228	21	70	34	21	2
Latossolo Bruno (Ferralsol)	3	694	110	250	62	55	102	26	5
Nitossolo Vermelho (Nitisol)	10	654	55	247	31	99	51	17	3
Argissolo Amarelo (Acrisol)	4	587	109	176	61	238	101	17	5
Latossolo Amarelo (Ferralsol)	3	576	110	181	62	243	102	19	5
Cambissolo Háplico (Cambisol)	4	538	79	315	44	146	72	17	3
Chernossolo Háplico (Chernozem)	1	537	113	287	64	175	103	16	7
Argissolo Amarelo (Acrisols)	7	505	64	253	36	242	59	17	3
Chernossolo Argilúvico (Chernozem)	5	455	78	380	44	165	72	16	3
Cambissolo Húmico (Cambisol)	9	436	55	341	31	222	51	24	3
Argissolo Vermelho Amarelo (Acrisol)	18	435	49	163	28	402	45	12	2
Latossolo Vermelho Amarelo (Ferralsol)	2	409	110	245	62	346	102	12	5
Neossolo Litólico (Leptosol)	1	163	113	77	64	761	103	7	7
Neossolo Quartzarênico (Arenosol)	7	41	64	26	36	933	59	7	3

(1) Embrapa (2006).

The effect of increased density and clay contents increased FC and to a greater extent, PWP for most of the subsurface horizons, with a mean value of 0.04 $cm^3 cm^{-3}$ in FC and of 0.07 $cm^3 cm^{-3}$ in PWP. The greatest moistures in FC and in PWP were observed in the soils derived from the following lithologies: muscovite garnet schist, siltstones and fine sandstones, parametamorphic, amygdaloidal basalt and mafic granulite, in which FC and PWP increased up to 0.13 and 0.18 $cm^3 cm^{-3}$, respectively, in relation to those observed in the surface horizons. This difference is principally due to the increase in the clay content (192 to 417 g kg^{-1}) (Table 6).

Table 5. Soil moisture at field capacity (FC), permanent wilting point (PWP), and available water content (AW), in soils grouped by lithology in the State of Santa Catarina

Lithology	FC		PWP		AW	
	Mean	SE[(1)]	Mean	SE	Mean	SE
	$cm^3 cm^{-3}$					
	Surface horizon					
Basaltic Andesite	0.54 ab	0.07	0.38 ab	0.05	0.16 abc	0.03
Basalt	0.51 a	0.02	0.38 a	0.01	0.13 bc	0.01
Dacite	0.50 ab	0.04	0.37 ac	0.03	0.13 abc	0.02
Shale	0.49 abc	0.04	0.34 abd	0.03	0.15 ab	0.02
Gneiss	0.49 abc	0.04	0.34 abd	0.03	0.15 ab	0.02
Mafic Granulite	0.48 abc	0.05	0.36 ab	0.03	0.12 bc	0.02
Rhyodacite	0.46 abc	0.07	0.36 abd	0.05	0.11 bc	0.03
Siltstones	0.44 abc	0.07	0.22 def	0.05	0.21 a	0.03
Hornblendite	0.42 abc	0.07	0.28 abde	0.05	0.14 abc	0.03
Amygdaloidal Basalt	0.41 bc	0.03	0.29 bde	0.02	0.13 bc	0.01
Muscovite Garnet Schist	0.41 abcd	0.07	0.27 bcde	0.05	0.14 abc	0.03
Parametamorphic	0.41 abcd	0.07	0.30 abde	0.05	0.10 bc	0.03
Migmatite	0.40 abcde	0.07	0.27 bcde	0.05	0.12 abc	0.03
Siltstones and fine Sandstones	0.35 bcde	0.07	0.21 ef	0.05	0.14 abc	0.03
Sandstones and Siltstones	0.34 cde	0.07	0.20 ef	0.05	0.14 abc	0.03
Botucatu Sandstone	0.25 def	0.05	0.14 fg	0.03	0.12 bc	0.02
Granite	0.21 ef	0.07	0.12 fg	0.05	0.08 bc	0.03
Recent Alluvial Deposits	0.16 f	0.04	0.07 g	0.03	0.09 c	0.02
	Subsurface horizon					
Basaltic Andesite	0.55 ab	0.05	0.44 ab	0.05	0.11 ns	0.02
Dacite	0.53 a	0.03	0.43 ab	0.03	0.11	0.01
Mafic Granulite	0.53 abc	0.03	0.43 ab	0.03	0.10	0.01
Basalt	0.52 a	0.01	0.43 a	0.01	0.09	0.01
Amygdaloidal Basalt	0.52 abc	0.02	0.42 a	0.02	0.10	0.01
Muscovite Garnet Schist	0.52 abc	0.05	0.43 ab	0.05	0.09	0.02
Parametamorphic	0.50 abc	0.05	0.42 abc	0.05	0.08	0.02
Rhyodacite	0.50 abc	0.05	0.43 abc	0.05	0.07	0.02
Hornblendite	0.48 abcd	0.05	0.35 abcd	0.05	0.13	0.02
Siltstones and fine Sandstones	0.48 abcd	0.05	0.39 abc	0.05	0.09	0.02
Shale	0.47 abcd	0.03	0.37 abc	0.03	0.10	0.01
Gneiss	0.47 abcd	0.03	0.37 abc	0.03	0.10	0.01
Migmatite	0.46 abcd	0.05	0.37 abcd	0.05	0.09	0.02
Siltstones	0.42 bcd	0.05	0.29 cde	0.05	0.13	0.02
Sandstones and Siltstones	0.36 def	0.05	0.24 def	0.05	0.12	0.02
Granite	0.28 efg	0.05	0.19 efg	0.05	0.08	0.02
Botucatu Sandstone	0.24 fg	0.05	0.14 fg	0.05	0.09	0.02
Recent Alluvial Deposits	0.20 g	0.03	0.10 g	0.03	0.10	0.01

(1) SE: standard error. Lower case letters compare the lithologies in each horizon by the LSD test (F<0.05).

Using lithology as a fixed effect, large differences were observed in FC and in PWP among soils with different lithologies. In the surface horizons, FC ranged from 0.16 $cm^3 cm^{-3}$ in the soils of recent alluvial deposits to 0.54 $cm^3 cm^{-3}$ in the soils derived from Basaltic Andesite, while PWP ranged from 0.07 to 0.38 $cm^3 cm^{-3}$ among these lithologies (Table 5). In the subsurface horizons with these same lithologies, FC ranged from 0.20 to 0.55 $cm^3 cm^{-3}$, and PWP from 0.10 to 0.44 $cm^3 cm^{-3}$. These differences result in an amplitude of 0.38 $cm^3 cm^{-3}$ in FC and of 0.31 $cm^3 cm^{-3}$ in PWP in the surface horizons and 0.35 $cm^3 cm^{-3}$ in FC and 0.34 $cm^3 cm^{-3}$ in PWP of the subsurface horizons (Table 5). This amplitude shows the importance of determination of water retention in soils that occur in a certain region

Table 6. Number of horizons (n), mean contents and standard error (SE) of the estimate for clay, silt, sand and organic matter (OM) in soils grouped by lithology in the State of Santa Catarina

Textural class		Clay		Silt		Sand		OM	
	n	Content	SE	Content	SE	Content	SE	Content	Se
		g kg^{-1}							
		Surface horizon							
Rhyodacite	4	669	132	308	91	23	70	55	34
Basalt	30	588	37	305	25	107	19	62	10
Dacite	9	587	76	354	53	59	40	60	21
Basaltic andesite	2	464	133	397	91	140	70	62	36
Migmatite	5	409	133	227	91	364	70	33	36
Shale	4	384	77	378	53	238	41	48	21
Mafic Granulite	3	373	94	273	65	353	50	50	26
Amygdaloidal basalt	11	355	50	451	35	194	27	57	14
Gneiss	2	335	133	261	91	405	70	34	36
Siltstones	1	323	133	322	91	355	70	38	36
Parametamorphic	1	266	133	194	92	540	70	45	36
Hornblendite	1	211	133	286	92	504	70	40	36
Muscovite garnet schist	2	206	133	344	92	449	70	36	36
Sandstones and siltstones	3	172	133	123	91	704	70	17	36
Siltstones and fine sandstones	3	171	132	359	91	470	70	19	34
Granite	4	140	132	143	91	717	70	21	34
Botucatu sandstone	5	137	94	79	65	784	50	14	26
Recent alluvial deposits	4	37	77	20	53	943	41	12	21
		Subsurface horizon							
Rhyodacite	3	798	112	183	77	19	63	22	5
Basalt	32	687	33	227	22	86	18	21	2
Muscovite garnet schist	7	624	112	159	77	218	63	16	5
Dacite	3	622	65	323	45	56	37	26	3
Amygdaloidal basalt	3	594	43	295	29	111	24	16	2
Basaltic andesite	4	592	112	279	77	129	63	26	5
Siltstones and fine sandstones	14	587	112	176	77	238	62	17	5
Migmatite	4	576	112	181	77	243	63	19	5
Parametamorphic	8	570	112	111	77	319	62	10	5
Mafic granulite	9	565	79	186	54	248	44	14	3
Shale	5	538	65	264	44	197	36	16	3
Gneiss	2	409	113	245	77	346	63	12	5
Siltstones	2	331	113	339	77	329	63	12	5
Hornblendite	3	294	113	303	77	404	63	19	5
Granite	3	247	112	168	77	585	63	16	5
Sandstones and siltstones	1	226	112	163	77	611	63	5	5
Botucatu sandstone	7	163	115	77	78	761	66	7	5
Recent alluvial deposits	3	41	65	26	45	933	37	7	3

when simulation models are used that involve soil physical-water processes.

In accordance with the differences observed in FC and in PWP, the AW content ranged from 0.08 to 0.21 $cm^3 cm^{-3}$ in the surface horizons. Nevertheless, the greater water retention capacity of some soils did not result in greater water availability to plants, since the AW contents were highest in soils derived from siltstones and lowest in those derived from granite and from recent alluvial deposits (Table 5). The AW content in the soils of the other lithologies was intermediate. The greater AW content in soils of Santa Catarina derived from siltstones occurred through more balanced particle size distribution, with clay, silt and sand contents very near the 1/3 ratio of each fraction, and also due to the greater contents of very fine sand (172 $g kg^{-1}$) in comparison to the soils of the other lithologies (5-99 $g kg^{-1}$). The lower AW content in soils of Santa Catarina derived from recent alluvial deposits, however, occurred due to their lower OM and very fine sand content (Table 6).

In the subsurface horizons, the mean AW contents ranged from 0.07 to 0.13 $cm^3 cm^{-3}$, but there was no significant difference due to their high variability in soils with the same lithology. Thus, in the subsurface horizons of the soils of SC, the mean AW content is 0.10 $cm^3 cm^{-3}$.

CONCLUSIONS

1. In the soils of Santa Catarina, water retention is greatest in clayey, silty and loamy soils, which have greater organic matter content, with small differences in water retention between the soil textural classes, due to higher field capacity and permanent wilting point. In contrast, water availability is greatest in the clayey loam and silty loam textural classes, also with highest organic matter contents, and lowest in the sand textural class. In addition, the greater water availability in the surface horizons in comparison to the subsurface horizons proves the importance of organic matter in water retention and availability.

2. Soil moisture at field capacity and at the permanent wilting point is highest in the Cambissolos (Cambisols) (especially in Cambissolos Húmicos), Nitossolos (Nitisols) and Latossolos (Ferralsols); intermediate in the Argissolos (Acrisols), Neossolos Litólicos (Leptosols) and Chernossolos (Chernozems); and lowest in the Neossolos Quartzarênicos (Arenosols). Greater water availability occurs in the Cambissolos Húmicos (Humic Cambisols) and the Neossolos Litólicos (Leptosols) located in the Planalto Serrano of Santa Catarina, mainly due to their high organic matter contents. Nevertheless, it is also important to remember that crops exploit distinct soil layers during their vegetative cycles and, for this reason, the quantity of water available also depends on the thickness of the soil horizons, especially of the surface horizons.

3. Water retention is highest in soils derived from extrusive igneous rocks from the Serra Geral Formation, metamorphic rocks, intrusive igneous rocks and fine-textured sedimentary rocks; it is intermediate in soils derived from medium-textured sedimentary rocks; and lowest retention occurs in soils derived from rocks or quartz-rich sedimentary deposits. The available water content is greatest in soils derived from siltstones and lowest in soils derived from granite and from recent alluvial deposits.

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