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Soil volumetric changes in natric soils caused by air entrapment following seasonal ponding and water table rises

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Abstract

Soil volumetric changes have been seldom studied in seasonally ponded soils subjected to periodic water table rises. In the Flooding Pampa of Argentina the topsoils develop significant swelling and shrinkage, despite their low percentages of total and expansible clay. We tested the hypothesis that: (a) the swelling of a Natraquoll and a Natraqualf of this region is caused by the wide change in water contents during ponding–drying cycles; and (b) soil swelling is accentuated by the effect of air entrapment ahead of the advance of soil wetting fronts. The relationship between the reciprocal of bulk density (i.e. soil specific volume), ν, and water content, θ, was determined in the laboratory (clod shrinkage curves) and in the field (repeated core sampling). Soil clods behaved in accordance to their inherent soil properties, with zero and residual shrinkage (slope $n = \delta\nu/\delta\theta < 1$) in both top horizons, and normal shrinkage (slope $n = \delta\nu/\delta\theta \approx 1$) throughout the water content range of Bt horizons. Unlike the clods, in the field the slope, n, was as high as 1.47–1.48 in top horizons, and 1.93–1.98 in both Bt horizons, showing the occurrence of *abnormal* soil swelling processes. Taking into account the narrow volumetric water content range found in the field (i.e. 0.25 v/v in both Bt horizons), this rejects our first proposed hypothesis. Soil air became trapped ahead of the advance of two field wetting fronts: (a) water table rises from depth and (b) surface ponded water. As a result, pore air volume increased during soil wetting, and was as high as 0.24–0.34 v/v, and 0.35 v/v at the maximum swelling limit of top and Bt horizons, respectively. Results show that air entrapment caused the swelling or "inflation" of soils, which agrees with our second hypothesis. However, the influence of air entrapment was more pronounced than a simple accentuation of swelling in Bt horizons. Air

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entrapment caused the whole soil to a depth of about 0.4 m to expand.

Keywords: Swelling soils; Volumetric analysis; Water regimes; Water table; Water flooding; Soil dynamics

1. Introduction

Soil volumetric changes associated with variations in water content are found in a range of soils of variable swell–shrink potential (Berndt and Coughlan, 1976; Crescimanno and Provenzano, 1999; Jayawardane and Greacen, 1987; Yule and Ritchie, 1980). Most of these studies were carried out in agricultural soils, characterised by a narrow range of water contents and subjected to different cropping systems. Considerably less attention received the occurrence of soil volumetric changes in seasonally ponded soils. These soils are seldom tilled, and are periodically affected by surface ponding and water table rises (Jacob et al., 1997; Lavado and Taboada, 1988).

The process of swelling was related to the intercalation of water in clay interlayers during soil wetting, which causes expansion in smectite and expansible interstratified soil minerals (Crescimanno and Provenzano, 1999; Low and Margheim, 1979; Parker et al., 1982; Schafer and Singer, 1976). Therefore, soil swell–shrink potential is highly correlated to the proportion of total clay, expansible clay and/or exchangeable sodium in soils. The build-up of entrapped pore air pressures is another possible soil swelling factor (Gäth and Frede, 1995; Parker et al., 1982). Air entrapment ahead of soil wetting fronts was studied in relation to its influence on soil water intake and the redistribution of water throughout the profile (Wang et al., 1997, 1998). When water infiltrates through the soil surface over a large area, soil air initially at local barometric pressure ($\approx$ 10 m of water) is displaced and probably compressed ahead of the wetting front by the penetrating water. Wang et al. (1997) determined the “air breaking value”, which is the maximum air capillary pressure at the time when air erupts from the soil surface. At this sufficiently high air pressure, the entrapped soil air breaks through the interconnected large pores of the wetted zone and escapes from the soil surface.

Air entrapment was related to the process of air slaking of dry, silty soil aggregates (Gäth and Frede, 1995), but the mechanism by which it causes soil swelling is less understood. Particularly, seasonally ponded soils represent a case where the influence of soil wetting fronts may be greater than in other soils. Our group have considerable experience in the Flooding Pampa of Argentina, a vast intrazonal area in which seasonally ponded soils occupy several thousands hectares (Fig. 1). In previous studies we found that even though these soils have low percentages of total and expansible clay, they still can develop noticeable changes in soil specific volume (i.e. 0.75–1.50 m^3 Mg^{-1}) during ponding–drying cycles (Rubio and Lavado, 1990; Taboada and Lavado, 1993; Taboada et al., 1988). Thus, other factors than the expansion of clay minerals could determine soil swelling in this area. In the present study, we investigated the nature of soil volumetric changes in seasonally ponded soils. We hypothesised that: (a) soil volumetric changes are due to the wide range of water content during ponding–dry-

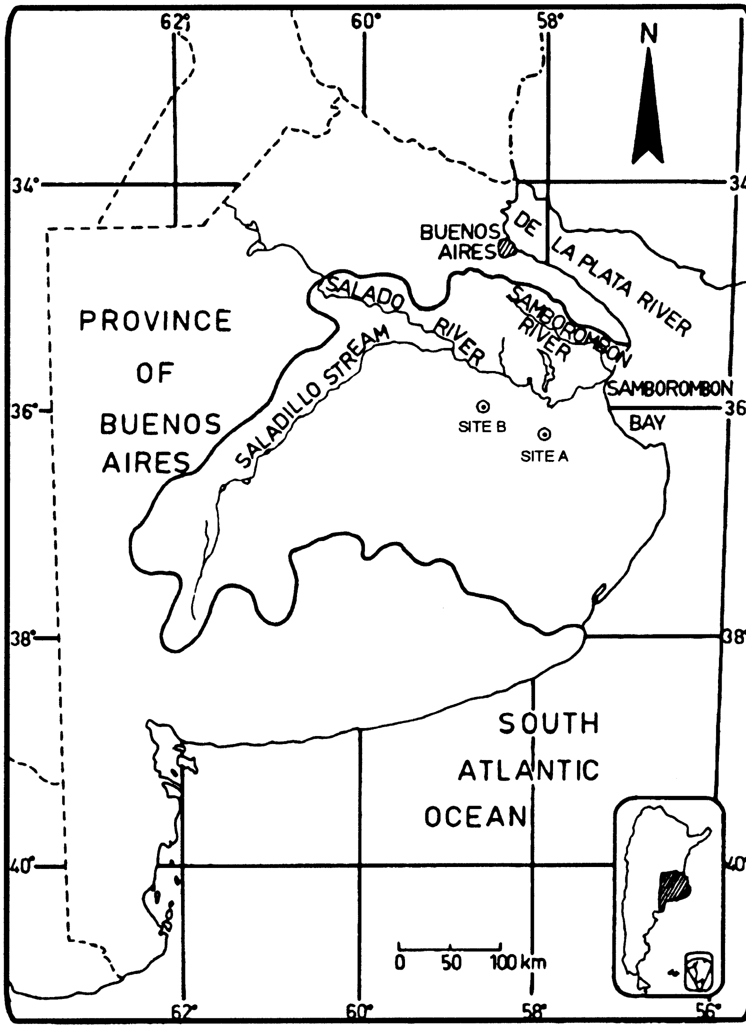

Fig. 1. Map of the province of Buenos Aires, showing the Flooding Pampa and the location of the study sites.

ing cycles; and (b) soil swelling is accentuated by the effect of air entrapment ahead of the advance of soil wetting fronts, caused either by the rise of water table or by surface ponding with rain water.

2. Shrinkage curves and shrinkage indices

Soil volumetric changes have been commonly investigated either by the shrinkage of natural clods on drying under controlled laboratory conditions (Coughlan et al., 1991;

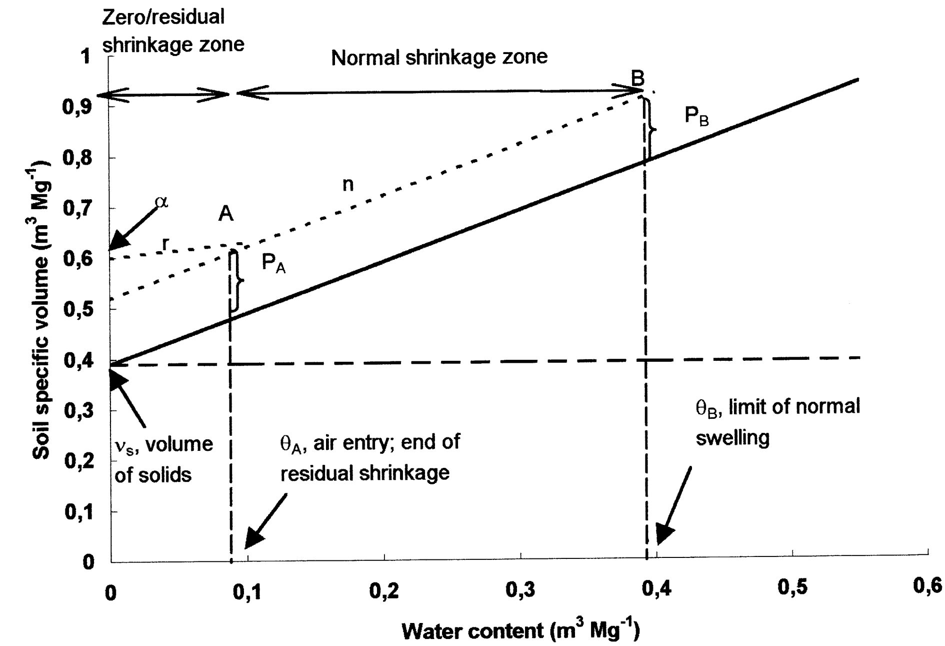

Fig. 2. Theoretical shrinkage curve showing the different shrinkage zones, and the indices and derived variables of shrinkage. Symbols are defined in Table 1.

Mc Garry and Daniells, 1987; Mc Garry and Malafant, 1987), or by the repeated sampling of soil cores in the field (Berndt and Coughlan, 1976; Jayawardane and Greacen, 1987). In both cases, the inverse of bulk density (i.e. soil specific volume, ν) is plotted to the volumetric water content (θ) of the soil. Fitted straight lines allow the identification of different shrinkage zones (Fig. 2). Normal shrinkage $(B \rightarrow A)$ is characterised by equivalent decreases in both ν and θ on drying, and so, by no air entrance to soil pores (Coughlan et al., 1991; Mc Garry and Daniells, 1987). In the drier range of the θ variation, soil ν decreases on drying are lower or even null. Residual shrinkage $(A \rightarrow \alpha)$ allows air entrance to soil pores, and hence the creation of air-filled porosity. In order to facilitate this discussion, Mc Garry and Daniells (1987) derived several indices and related variables from the shrink data of natural soil clods (Fig. 2; Table 1).

3. Material and methods

3.1. Description of the area and studied soils

In the Flooding Pampa of Argentina, most of the soils were developed from loess-like sediments, and land-form is characterised by its extreme flatness. The most frequent types of soils in this region are Natraquolls (28,000 km^2) and Natraqualfs (11,000 km^2)

Table 1
Indices and related variables from the shrink data of natural soil clods (Mc Garry and Daniells, 1987)

Indices	
θ_B	θ at the limit of normal swelling
θ_A	θ at the air entry point, i.e. the end of residual shrinkage
n	slope of the line B → A (normal shrinkage)
r	slope of the line A → α (residual shrinkage)
ν_B	specific volume at the limit of normal swelling
ν_A	specific volume at the air entry point
α	specific volume at zero water content
P_B	specific volume of air filled pores at B
P_A	specific volume of air filled pores at A
P_α	specific volume of air filled pores at α
$\theta_B - \theta_A$	difference between θ at the limit of normal swelling and θ at the air entry point, i.e. range of θ in the normal shrinkage zone

(Salazar Lea Plaza and Moscatelli, 1989). The climate is temperate and rainfall (average 1000 mm per year) has an even distribution throughout the year, but evapotranspiration has large fluctuations among seasons (from 3 to 12 mm per day). Most of this area is usually ponded during winter–spring periods, when two wetting fronts may occur simultaneously: (a) the rise of water table from depth, and (b) the downward movement from surface ponded water (Lavado and Taboada, 1988).

Soil samples were taken in two sites covered with untilled grasslands (Fig. 1): site A: a General Guido Series soil (Typic Natraquoll); and site B: a Chelforó Series soils (Mollic Natraqualf). The main properties of both soils are given in Table 2. Both of them have no vertic features (i.e. slickensides, visible cracks, etc.), throughout their profile. Taboada et al. (1988) determined the mineralogy of the fraction to be less than 2 μm (X-ray diffraction) in the soil of site A. It is mainly composed by illite throughout the profile, while smaller amounts of interstratified smectitic materials and a negligible amount of kaolinite in the surface horizons. The mineralogy of site B is similar, as reviewed by Lavado and Camilión (1984). This mineralogy is typical for most sodic soils of the region.

Table 2
Soil properties in surface (Ah and E) and Bt horizons of the studied soils

Horizon	Depth (m)	Structure	Clay < 2 μm (% w/w)	Silt 2–50 μm (% w/w)	pH (in paste)	Org. C (% w/w)	SAR
Typic Natraquoll, General Guido Series							
Ah	0–0.13	subang. blocks	22.8	41.3	6.0	3.5	6.8
Bt	0.21–0.32	prisms	34.0	36.7	7.2	0.5	17.4
Typic Natraqualf, Chelforó Series							
E	0–0.11	subang. blocks	18.5	42.0	8.2	1.2	7.8
Bt	0.19–0.40	prisms	48.3	37.2	9.0	0.9	33.9

3.2. Assessment of soil volumetric changes

Soil volumetric changes were assessed by means of both the shrinkage of natural clods in the laboratory, and the repeated sampling of soil cores in the field. To accomplish the laboratory determinations, samples of surface (Ah and E) and Bt horizons of both soils were taken at moist conditions during the summer. The samples were partially dried in the laboratory, so that natural clods (2–3 cm diameter) could be easily separated by hand. Twenty aggregates were used to build up the shrinkage curves. The clods were wetted over filter paper in contact with water saturated cotton. From saturation, five clods were removed at 2-day intervals during air-drying to determine their volume following the method for bulk density of aggregates described by Burke et al. (1986). It consists in submerging the aggregates in kerosene for 24 h, and drying them quickly on blotting paper just until the peripheral film of kerosene was eliminated. The volume of aggregates was measured by hydrostatic upthrust in the kerosene. Clods were oven-dried to determine their gravimetric water content.

Cores were taken from both soils on different dates, thus yielding an ample range of soil water contents. Soil samples were collected using cores (9 cm diameter, 10 cm length) of the same type as Yule and Ritchie's (1980). The water content (oven-drying at 105–110°C) and the bulk density of each soil core were determined within 24 h of sampling.

The inverse of soil bulk density, i.e. specific soil volume, ν, was plotted against the gravimetric water content, θ. Straight lines were fitted by regression for each shrinkage zone, in the θ–ν relationships obtained with both laboratory and field data. We calculated the indices and derived variables of shrinkage (Fig. 2; Table 1) in both topsoil and Bt horizons, and differences between them were evaluated using one-way analysis of variance. The clods were wetted by capillary rise, thus avoiding air confinement. Thus, differences in clod shrinkage indexes of different soils and horizons indicated the effect of inherent soil properties (i.e. exchangeable Na and clay percentages). We calculated the same indices to our swell–shrink field data. This procedure was judged reliable, taking into account the close θ–ν relationships ($R^2 > 0.86$; $P < 0.001$) always fitted to field data. In order to compare shrinkage indices obtained in natural clods with those in field cores, we calculated the percentage variation from the clods to the field:

$$\Delta\% = \left[(\text{field index} - \text{clod index}) / \text{clod index} \right] \cdot 100 \qquad (1)$$

This index indicates the influence of a number of factors, such as plant roots, aggregated structure, air entrapment, and so on, only present in the field.

3.3. Assessment of the influence of wetting fronts in the field

The influence of the wetting front caused by water table rise was evaluated during a typical climatic cycle (March 1991 to March 1992) at the site of soil A (Guido Series), where we recorded the depth of water table in three wells. Water table depth data were related to soil ν and the specific volume of air filled pores (P) of the three top horizons of soil A. Soil P was calculated from the water-filled pores, and considering the dry weight and the total pore space in each field core. Soil particle densities were determined with a picnometer (Burke et al., 1986).

The individual influence of surface ponding was evaluated by means of a field experiment carried out during summer when the water table was deep. Three 1-m^2 field plots were delimited with metal walls (25-cm depth), and the soil inside them watered with water taken from a nearby pond. The height of surface water was kept at about 5 cm during 24 h. Soil ν, θ and P were determined in the Ah horizon before, during and after the experiment. For comparison, three monoliths taken from the same soil were wetted by capillary rise, and their ν, θ and P also determined. The effect of surface ponding on soil ν, θ and P was evaluated by analysis of variance.

4. Results and discussion

4.1. Shrinkage of natural clods

The shrinkage characteristics of natural clods had two distinct shrinkage zones (i.e. zero and residual shrinkage) in surface and Bt horizons (Fig. 3a–d; Table 3). At the surface, soil texture was loam in the General Guido site and silt loam in Chelforó site (Table 2). As previously found, both soils had low proportion of expansible clay (Lavado and Camilión, 1984; Taboada et al., 1988). Therefore, surface clods had slopes, *n*, of about 0.5–0.6 (Table 3) showing residual shrinkage during most of the drying phase. The specific volume of air filled pores increased as the clods dried ($P_B < P_A < P_\alpha$). Several clod shrinkage indices differed significantly between sites. For instance, the clods of site B had significantly higher $\theta_B - \theta_A$ range and maximum specific volume, ν_B (Table 3). Likely, the lower amount of organic carbon in topsoil of site B favoured clod volumetric expansion, because of the weaker bonding between soil particles and aggregates (Crescimanno and Provenzano, 1999; Schafer and Singer, 1976; Taboada et al., 1988).

The clods of both Bt horizons had normal shrinkage (slope *n*, about 1) over most of their water content variation range (Fig. 3c and d), showing the shrinkage characteristic of other extensively swelling soils (Crescimanno and Provenzano, 1999; Yule and Ritchie, 1980). As the range of θ in the zero shrinkage zone, $\theta_A - \theta_\alpha$, was narrow, the specific volume of air filled pores at the end of drying, P_α, only reached about 0.20 in both Bt horizons (Table 3). The clods of site B retained more water than those of soil A, and so they swelled over a wider water content range ($\theta_B - \theta_A$). This considerable volumetric expansion can be attributed to its higher sodium adsorption ratio (Table 2), which increases the osmotic component of the clay–water system (Low and Margheim, 1979). Like in topsoil, the clods of both Bt horizons also behaved in accordance to their inherent soil properties.

4.2. Soil volume changes in the field

The θ–ν relationships obtained in field cores differed greatly from those obtained in clod shrinkage curves (Fig. 4a–d). This is also shown by the often high variations, Δ%,

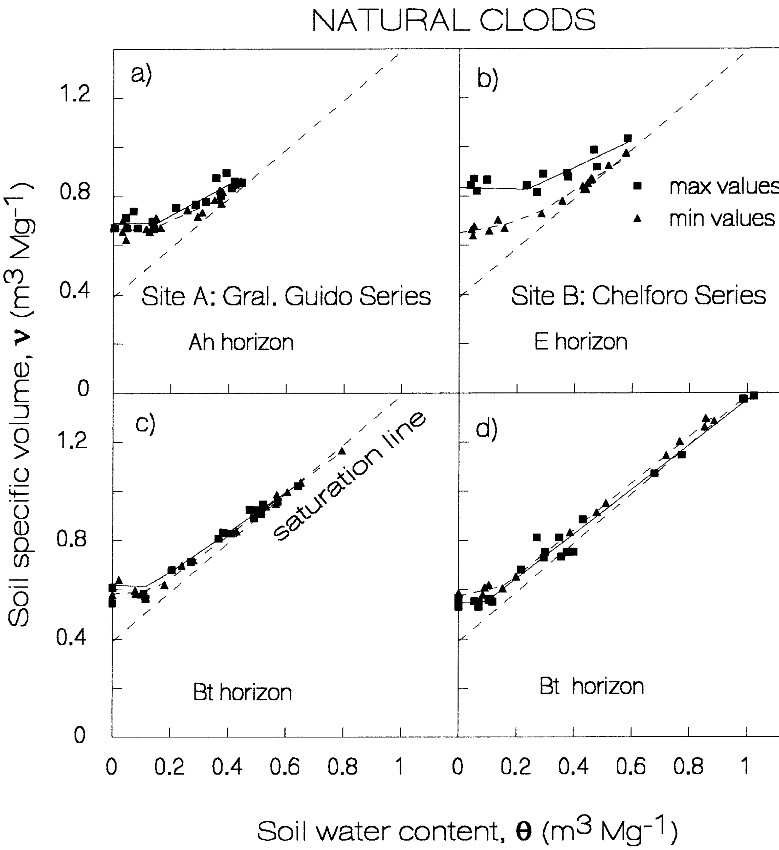

Fig. 3. Shrinkage curves of natural clods of surface (a and b) and Bt horizons (c and d) of soils in sites A (Typic Natraquoll) and B (Mollic Natraqualf).

in the indices comparing the clods with the field (Table 4). Most indices had positive Δ% values, because of higher values in the field than in the clods. Only the range of water content variation during the normal phase ($\theta_B - \theta_A$) varied negatively. For instance, the range of water content was as narrow as about 0.20 v/v in both surface horizons, and 0.17–0.28 v/v in both Bt horizons (Table 4). This indicates that in our study area soil volumetric changes were not due to the wide range of water content during ponding–drying cycles, which rejects our first proposed hypothesis. Other authors also found significantly less shrinkage in confined cores compared with clods (Crescimanno and Provenzano, 1999; Mitchell and Van Genutchen, 1992), in part because of a different structural arrangement and porosity of the clods and cores. Conversely, the clods of our soils always had less shrinkage than field cores. Moreover, $\theta - \nu$ functions fitted in the field deviated from the theoretical saturation line as the soils wetted (Fig. 4a–d), unlike the functions fitted in the clods which deviated as the soils dried (Fig. 3a–d). In a conceptual model, Toll (1995) proposes that “initially

Table 3
Shrinkage indices in clods of surface and Bt horizons of the soils of sites A and B

Indices	Units	Site A: Typic Natraquoll			Site B: Mollic Natraqualf			Site A vs. Site B	
		General Guido Series			Chelforó Series			Surface	Bt
		Horizons			Horizons			signif.	signif.
		A	Bt	P <	E	Bt	P <		
θ_B	(m^3 Mg^{-1})	0.410	0.715	**	0.580	0.955	***	***	*
θ_A	(m^3 Mg^{-1})	0.131	0.135	ns	0.215	0.127	*	**	ns
n		0.572	0.840	*	0.642	0.924	*	ns	ns
r		−0.064	−0.027	ns	0.096	0.171	ns	ns	ns
ν_B	(m^3 Mg^{-1})	0.840	1.095	*	0.985	1.345	***	**	**
ν_A	(m^3 Mg^{-1})	0.679	0.604	*	0.754	0.585	**	ns	ns
α	(m^3 Mg^{-1})	0.681	0.600	ns	0.751	0.560	*	ns	ns
P_B	(m^3 Mg^{-1})	0.040	0.005	ns	0.030	0.015	ns	ns	ns
P_A	(m^3 Mg^{-1})	0.159	0.089	*	0.159	0.078	ns	ns	ns
P_α	(m^3 Mg^{-1})	0.291	0.220	*	0.371	0.180	ns	ns	ns
$\theta_B - \theta_A$	(m^3 Mg^{-1})	0.280	0.581	*	0.365	0.828	*	**	*

***, **, and * mean significant differences between horizons at $P < 0.001$, $P < 0.01$, and $P < 0.05$, respectively.
ns means not significantly different between soils.

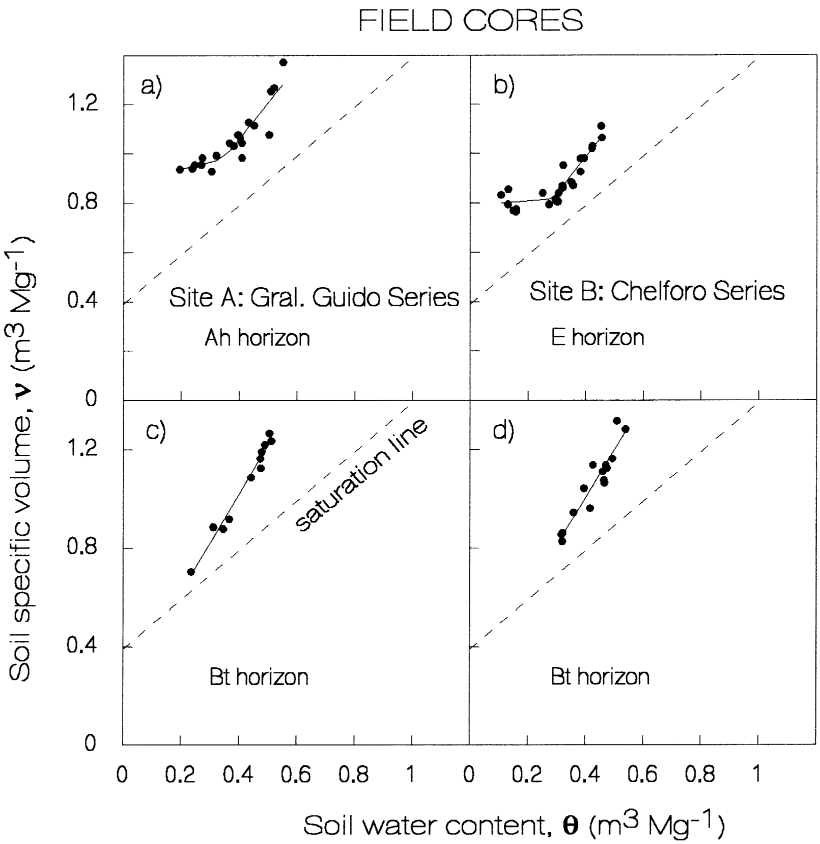

Fig. 4. Soil specific volume—water content relationships from repeated core sampling in the field of surface (a and b) and Bt horizons (c and d) of soils in sites A (Typic Natraquoll) and B (Mollic Natraqualf).

saturated” soils subjected to drying decrease more their volume than rewetted and then dried soils (i.e. “overdried”). We think that “overdrying” due to rewetting was not the cause of the different soil volumetric behaviour between the clods and the cores. Both of them were “field soils”, and then subjected to wetting and drying cycles. The specific volume of air-filled pores at the end of swelling, P_B, had the highest variation, Δ%, from the clods to the field (Table 4). This index, which never surpassed 0.04 v/v in wet clods, was as high as 0.20–0.35 v/v in surface and Bt horizons sampled by cores in the field. This shows a process of air entrapment within soil pores during soil wetting (Fig. 4a–d). This may be explained by the occlusion of pore air by pore water when the degree of saturation increases to near 80% (Chen and Yu, 1995). As a result, in the field air filled porosity was the highest at the maximum swelling limit ($P_B > P_A > P_\alpha$). Soil swelling under such conditions must be regarded as a process of “inflation” of pore space by entrapped air (Gäth and Frede, 1995). The influence of trapped air can be assessed from the magnitude of slopes, n (Table 4). They were about 1.5 in both surface

Table 4
Shrinkage indices in field soil cores of surface and Bt horizons of the Chelforó (Mollic Natraqualf) and the Guido (Typic Natraquoll) soils, and percentage variations of these indices (Δ%) from the clods to the field

Indices	Units	Surface horizons				Bt horizons			
		Chelforó	Δ%	Guido	Δ%	Chelforó	Δ%	Guido	Δ%
θ_B	(m^3 Mg^{-1})	0.552	−4.8	0.455	11.0	0.538	−43.7	0.512	−28.4
θ_A	(m^3 Mg^{-1})	0.344	60.0	0.283	116.9	0.316	148.8	0.236	75.5
n		1.470	129.2	1.482	159.3	1.929	108.8	1.980	135.9
r		0.280	193.0	0.082	−226.7				
ν_B	(m^3 Mg^{-1})	1.280	29.9	1.070	27.4	1.273	−5.4	1.239	13.2
ν_A	(m^3 Mg^{-1})	0.977	29.6	0.815	20.0	0.845	44.6	0.691	14.5
α	(m^3 Mg^{-1})	0.881	17.3	0.792	16.4				
P_B	(m^3 Mg^{-1})	0.338	1026.7	0.235	487.5	0.355	2266.7	0.347	6840.0
P_A	(m^3 Mg^{-1})	0.243	53.3	0.152	−4.4	0.149	92.3	0.075	−15.7
P_α	(m^3 Mg^{-1})	0.491	32.3	0.412	41.6				
$\theta_B - \theta_A$	(m^3 Mg^{-1})	0.208	−43.0	0.172	−38.5	0.222	−73.2	0.276	−52.5

horizons, and about 2 in both Bt horizons (Fig. 4a–d; Table 4). Because these slopes are higher than 1, our soil volumetric changes can be considered *abnormal*.

The surface horizons of both soils had two distinct swell–shrink zones (Fig. 4a and b). Below the air entry point, θ_A, there were zero volumetric variations, while above this point, there were *abnormal* volumetric variations. Despite their different clay percentages, pH and SAR values (Table 2), both Bt horizons showed similar linear θ–ν relationships in the field (Fig. 4c and d). Taking into account the slopes, n of about 2, the effect of trapped air in them was more pronounced (Table 4). Unlike the clods, the inherent soil properties (e.g. soil texture, clay percentage, sodium adsorption ratio) exerted virtually no influence on soil swell–shrink capacity in the field. Soil swelling was accentuated by air entrapment in both top horizons, which accepts our second hypothesis (Table 4; Fig. 4). However, in both Bt horizons the influence of air entrapment was more pronounced than a simple accentuation of swelling, causing the whole volumetric expansion. Parker et al. (1982) also found soil swelling attributable to air entrapment, but in their case it only accounted for 8–59% of the total expansion of Bt samples.

4.3. Sources of trapped air

In the study area, during winter–spring the water table rises from more than 2-m depth up to about 0.65 m, where the bottom of the impervious Btk horizon checks water table rises further. Fig. 5 shows the variation of water table depth and the specific volume of air filled pores in the Ah, BA and Bt horizons, showing the typic water regime of the region. A conceptual model describing the changes taking place in the soil profile is proposed (Fig. 6). At the start of well recording (March 1991), the water table was as deep as usual at the end of a summer period (Lavado and Taboada, 1988), and there is groundwater recharge by rain water through preferential flow paths (Dreccer and Lavado, 1993). The soil is at a “bio-opened” condition, as defined by Chen and Yu

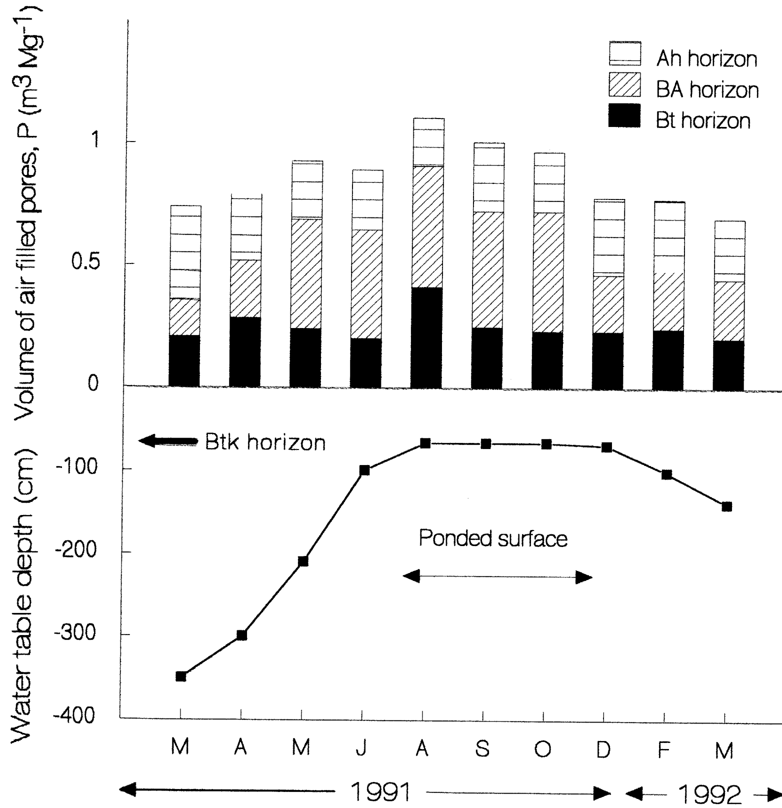

Fig. 5. Water table depth and volume of air filled pores in the upper three horizons of the soil of site A (typic Natraquoll).

(1995), and its condition is represented by Fig. 6a. During autumn and winter, the water table rose close to the soil surface, and in August 1991, it reached the bottom of the impervious Btk horizon. This horizon prevents further water table rises up to the soil surface, so that the groundwater below it is under pressure (Lavado and Taboada, 1988). The specific volume of air filled pores made a peak in the Bt horizon, showing air entrapment ahead of the rising water table. The soil condition changed to "air-occluded", which greatly reduces the dissipation of pore pressure (Chen and Yu, 1995). Thus, the air within soil pores could not escape to the atmosphere and became trapped, likely under pressure. The rain excess under such conditions creates a "perched" water table over the impervious Btk horizon, which results in surface ponding with rainwater during winter and most of spring. During ponding, trapped air was redistributed upward from the Bt horizon to the overlying BA and Ah horizons and a rapid increase in air filled porosity (i.e. total porosity less water filled porosity) was observed at the same time. This causes soil swelling due to "air inflation", as represented by Fig. 6b.

As soon as water ponding was over in the next summer, *P* decreased and returned again to its original value because of the rapid dissipation of pore pressure by rapid

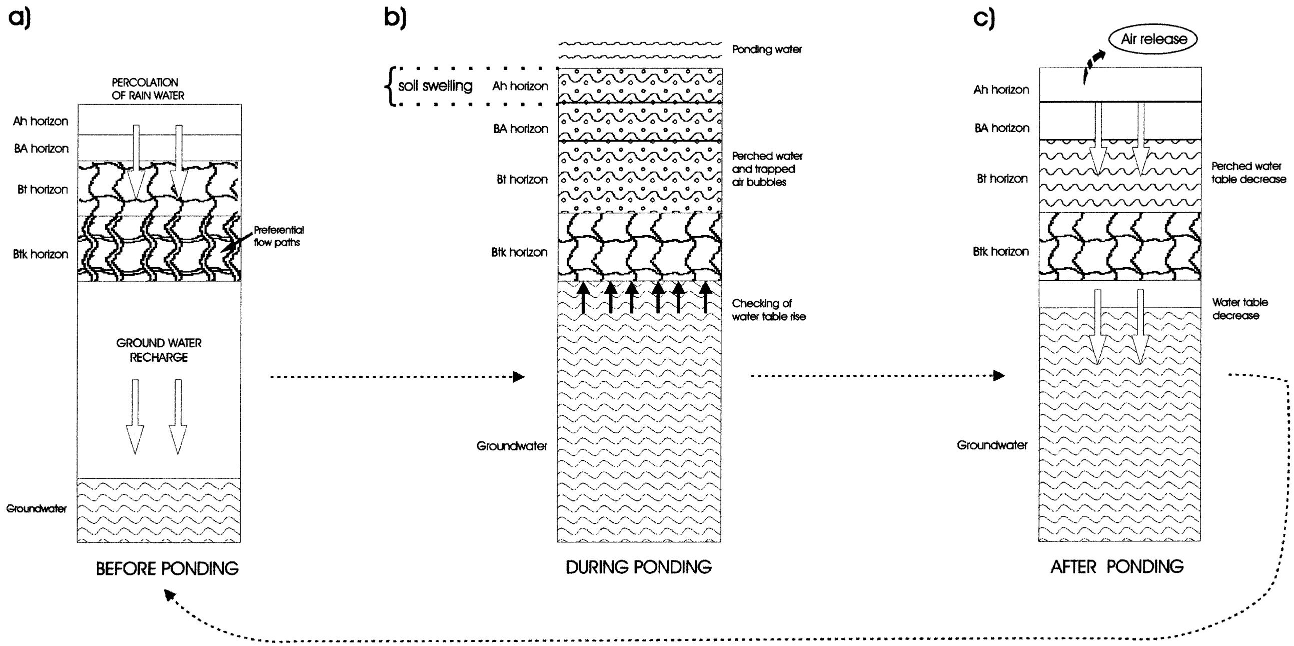

Fig. 6. Conceptual model describing the process of soil swelling because of air entrapment. (a) Before ponding: free water and air movements throughout the profile (bio-opened system); (b) during ponding: soil swelling by air trapped within water table perched over the impervious Btk horizon (air-occluded system); (c) after ponding: soil shrinkage after perched water and water table decreases, and rapid air escape to the atmosphere.

escape of continuous pore air throughout the soil (Chen and Yu, 1995). It is shown by Fig. 5 and represented by Fig. 6c. These results show that the rise of water table from depth is a major source of air entrapment and soil swelling in this area.

Results on the field experiment of ponding show the relative importance of surface ponding on soil swelling (Table 5). Before the experiment, the soil was near field capacity. After 24 h surface ponding, both volumetric water content and soil specific volume increased significantly, but P did not change. This indicates that air became trapped in the wet soil. After ponding, trapped air escaped to the atmosphere, air-filled porosity decreased significantly, and soil ν returned again to the value before ponding. Soil monoliths wetted by capillarity showed the typical displacement of air by water (Table 5). Under the unconfined conditions of this experiment, the Ah horizon of the monoliths behaved like clods in the laboratory. Results of this field experiment show that surface ponding is also an important source of abnormal volumetric changes by air entrapment.

In a laboratory experiment, Gäth and Frede (1995) found a process of soil “inflation” under quick saturation of quartz, a rigid material. Our field results seem to be another instance of the same process. Our unusually high entrapped air volumes at the maximum swollen condition, P_B, (Table 4) can be regarded as the result of two coincident wetting fronts during winter–spring periods (Lavado and Taboada, 1988). Air bubbles entrapped between the ponded soil surface and the rising water table could not escape, showing that the “air breaking value” was not reached in our study site (Wang et al., 1998). This explains why air entrapment exerted so great an influence on the swelling of our soils.

Some consequences of air entrapment are in the same direction than our previous results in the same experimental site. Dreccer and Lavado (1993) found preferential flow paths through which rainwater infiltrates and redistributes in this soil. This agrees with experimental results of Wang et al. (1998), who also showed wetting front instability and fingering processes because of air compression ahead of confined wetting fronts. We found topsoil loosening and macroporosity recovery after ponding because of the mellowing of topsoil aggregates (Taboada and Lavado, 1993; Taboada et al., 1999). Soil mellowing consists in the partial slaking of aggregates carried to high water contents (Grant and Dexter, 1990). Topsoil structural improvement found during ponding in this site thus appears as a consequence of soil inflation (Gäth and Frede, 1995).

We can then conclude that air entrapment due to water table rises from depth and surface ponding was the main factor determining the swelling of soils. While most soils have *less than normal* volumetric changes, our studied soils developed *abnormal*

Table 5
Soil specific volume (ν), volumetric water content (θ_v) and the specific volume of air filled pores (P) in the Ah horizon of the Guido soil, as a result of surface ponding (field experiment) and capillarity moistening

		ν ($m^3\ Mg^{-1}$)	θ_v ($m^3\ m^{-3}$)	P ($m^3\ m^{-3}$)
Surface ponding	before	1.35 b	0.250 c	0.462 a
	during	2.23 a	0.322 bc	0.501 a
	after	1.47 b	0.390 b	0.341 b
Capillarity moistening		1.16 b	0.526 a	0.136 c

swelling. These results may contribute to develop a framework to explain the structural behaviour of seasonally ponded soils.

References

Berndt, R.D., Coughlan, K.J., 1976. The nature of changes in bulk density. Aust. J. Soil Res. 15, 27–37.

Burke, W., Gabriels, D., Bouma, J., 1986. Soil Structure Assessment. A.A. Balkema, Publishers, Rotterdam.

Chen, Y.J., Yu, P.J., 1995. Pore pressure dissipation features of an unsaturated compacted soil. In: Alonso, E.E., Delage, P. (Eds.), Unsaturated Soils. A.A. Balkema, Rotterdam, pp. 439–445.

Coughlan, K.J., Mc Garry, D., Loch, R.J., Bridge, B., Smith, G.D., 1991. The measurement of soil structure—some practical initiatives. Aust. J. Soil Res. 29, 869–889.

Crescimanno, G., Provenzano, G., 1999. Soil shrinkage characteristic curve in clay soils: measurement and prediction. Soil Sci. Soc. Am. J. 63, 25–32.

Dreccer, M.F., Lavado, R.S., 1993. Influence of cattle trampling on preferential flow paths in alkaline soils. Soil Use Manage. 9, 143–148.

Gäth, S., Frede, H.G., 1995. Mechanisms of air slaking. In: Hartge, K.H., Stewart, B.A. (Eds.), Soil Structure: Its Development and Function. C.R.C Lewis Publishers, Boca Raton, Florida, pp. 159–173.

Grant, C.D., Dexter, A.R., 1990. Air entrapment and differential swelling as factors in the mellowing of moulded soil during rapid wetting. Aust. J. Soil Res. 28, 361–369.

Jacob, J.S., Griffin, R.W., Miller, W.L., Wilding, L.P., 1997. Aquerts and aquertic soils: a querulous proposition. In: Vepraskas, M.J., Sprecher, S.W. (Eds.), Aquic Conditions and Hydric Soils: The Problem Soils. SSSA Special Publication, Number 50. Soil Science Society of America Publishers, Madison, Wisconsin, USA, pp. 61–77.

Jayawardane, N.S., Greacen, E.L., 1987. The nature of swelling in soils. Aust. J. Soil Res. 25, 107–113.

Lavado, R.S., Camilión, M.C., 1984. Clay minerals in Argentine salt-affected soils. Clay Res. 3, 68–74.

Lavado, R.S., Taboada, M.A., 1988. Water, salt and sodium dynamics in Natraquoll in Argentina. Catena 15, 577–594.

Low, P.F., Margheim, J.F., 1979. The swelling of clay: I. Basic concepts and empirical equations. Soil Sci. Soc. Am. J. 43, 473–481.

Mc Garry, D., Daniells, 1987. Shrinkage curves indices to quantify cultivation effects on soil structure of a Vertisol. Soil Sci. Soc. Am. J. 51, 1575–1580.

Mc Garry, D., Malafant, K.W.J., 1987. The analysis of volume change in unconfined units of soil. Soil Sci. Soc. Am. J. 51, 290–297.

Parker, J.C., Amos, D.F., Zelazny, L.W., 1982. Water adsorption and swelling of clay minerals in soil systems. Soil Sci. Soc. Am. J. 46, 450–456.

Rubio, G., Lavado, R.S., 1990. Efectos de alternativas de manejo pasturil sobre la densidad aparente de un suelo con horizonte nátrico. (Effect of different grazing management systems on the bulk density of a Natraqualf). Ciencia del Suelo 7, 79–82.

Salazar Lea Plaza, J.C., Moscatelli, G., 1989. Mapa de Suelos de la Provincia de Buenos Aires. Escala 1:500 000 (Soil Map of the Province of Buenos Aires. Scale 1: 500 000). SEAGyP-INTA, Buenos Aires.

Schafer, W.M., Singer, M.J., 1976. Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. Soil Sci. Soc. Am. J. 40, 557–562.

Taboada, M.A., Lavado, R.S., 1993. Influence of trampling on soil porosity under alternate dry and ponded conditions. Soil Use Manage. 9, 139–143.

Taboada, M.A., Lavado, R.S., Camilión, M.C., 1988. Cambios volumétricos en un Natracuol tipico. (Soil volumetric changes in a Typic Natraquoll). Ciencia del Suelo 6, 151–157.

Taboada, M.A., Lavado, R.S., Svartz, H., Segat, A., 1999. Structural stability changes in a grazed grassland Natraquoll of the Flooding Pampa (Argentina). Wetlands 19, 50–55.

Toll, D.G., 1995. A conceptual model for the drying and wetting of soil. In: Alonso, E.E., Delage, P. (Eds.), Unsaturated Soils. A.A. Balkema, Rotterdam, pp. 805–810.

Wang, Z., Feyen, J., Nielsen, D.R., van Genutchen, M.Th., 1997. Two-phase flow infiltration equations accounting for air entrapment effects. Water Resour. Res. 33, 2759–2767.

Wang, Z., Feyen, J., van Genutchen, M.Th., Nielsen, D.R., 1998. Air entrapment effects on infiltration rate and flow instability. Water Resour. Res. 34, 213–222.

Yule, D.F., Ritchie, J.T., 1980. A. Soil shrinkage relationships of Texas vertisols: I. Small cores. Soil Sci. Soc. Am. J. 44, 1285–1291.