Soil Shrinkage Characteristics in Swelling Soils

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The objectives of this presentation are to:

- understand soil swelling and shrinkage mechanisms, and the development of desiccation cracks;
- distinguish between soils having different magnitude of swelling, as well as the consequences on soil structural behaviour;
- know methods to characterize soil swell/shrink potential;
- construct soil shrinkage curves, and derive shrinkage indices, as well to apply them to assess soil management effects.

The "physics" of soil physics traditionally assumes that soils have rigid behavior; that means relatively stable relations between their solid and pore volume. In the well-known schematic diagram of the three phase system, the solid phase remains stable while the volumes of water and air vary conversely within pore space (Figure 1).

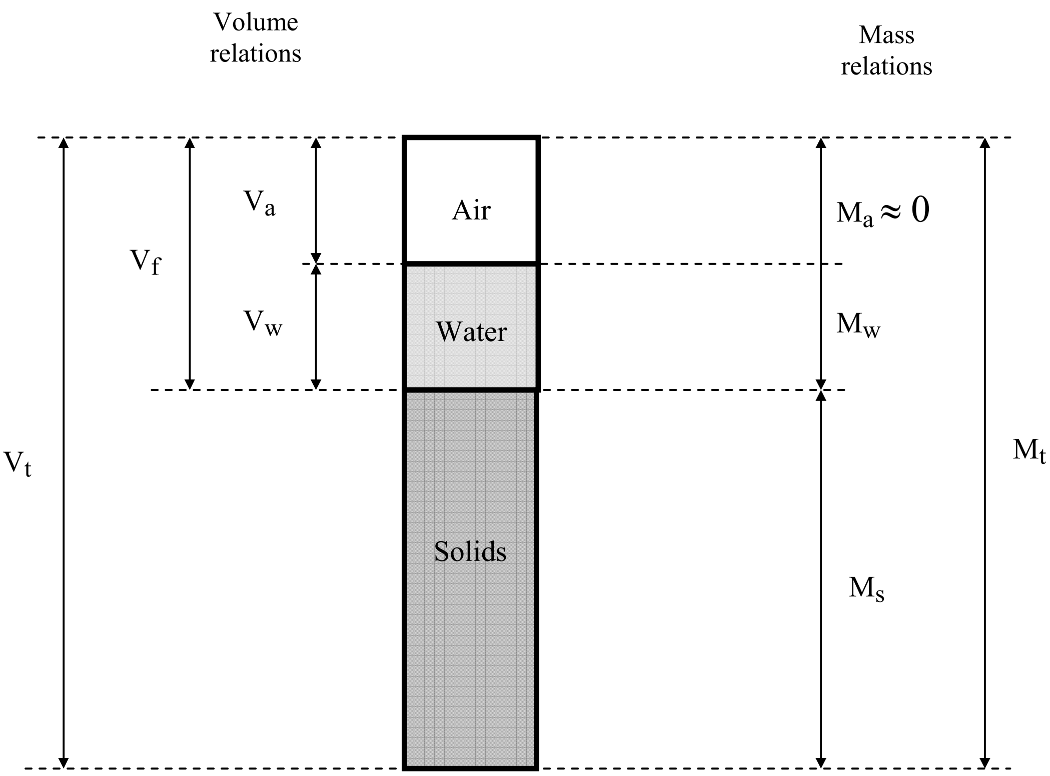

Figure 1. Schematic diagram of the soil as a three phase system

When a rigid soil dries, a given volume of air enters to the pore space in replacement of an equivalent volume of water. On the basis of this theoretical

approach several methodologies have been developed. For instance, the determination of pore size distribution using the water desorption method (Burke et al. 1986).

$$\delta V_w = \delta V_a \qquad [1]$$

Therefore, air-filled porosity increases as a rigid soil dries. As can be observed in Figure 2, rigid or non swelling soils do not change their specific volume, ν, and hence, their bulk density ρ_b during their water content θ variation range. Rigid or non swelling soils are usually coarse – textured, organic matter – poor, and hard to till. They also have low aggregate stability, high module of rupture, and low resilience after a given damage (e.g. compaction by agricultural traffic). They are considered to have hard-set behavior. Figure 3 shows a non swelling sandy loam (Haplic Phaeozem) of the Argentine Pampas. After several years of disc plowing, a hard plow pan is developed in the subsoil.

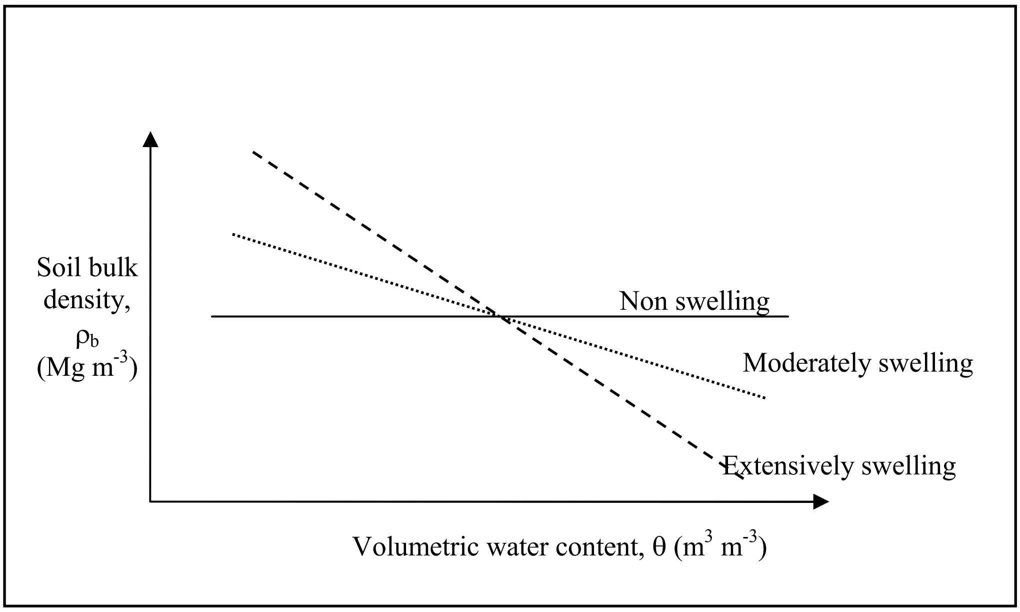

Figure 2. Schematic variation of soil bulk density in non swelling (rigid), moderately swelling and extensively swelling soils.

In contrast, extensively swelling soils undergo significant bulk density, ρ_b, variations during their water content, θ, variation range. They are usually fine – textured, with smectitic type of clays. They develop desiccation cracks on drying, which confers them high resilience, and little tillage requirement. They are considered to have self-mulch behavior. Figure 4 shows an extensively swelling soil, a Vertisol cropped to soybean in the Argentine Mesopotamia. Their self mulching facilitates their management under continuous zero tillage.

Figure 3. A hard plow pan developed in the subsoil of a sandy loam (Haplic Phaeozem) of the Argentine Pampas.

Figure 4. Extensively swelling Vertisol of the Argentine Mesopotamia, cropped to soybean using zero tillage.

Generally, most agricultural soils in the world develop only moderate volumetric changes during wetting and drying. This occurs provided the soil has less 8 % swelling clays (Dexter 1988). Although moderate, this swelling is highly important to the regeneration of soil structure after a given damage.

Processes taking place in swelling soils during drying and wetting

Different processes take place when a swelling soil dries or swells. On drying the soil decreases its volume by shrinkage, and desiccation cracks appear because of internal stresses in the shrunken and dried soil mass. These cracks are created in pre-existing planes of weakness within soil clods. As a result of shrinkage, soil decreases its height by subsidence. On wetting the soil increases its volume by swelling, the cracks are closed, and soil level rises. The process of swelling is mainly caused by the intercalation of water molecules entering to the inter-plane space of smectitic clay minerals (after Low and Margheim 1979, Schafer and Singer 1976, Parker et al. 1982). An schematic visualization of this process is depicted by Figure 5.

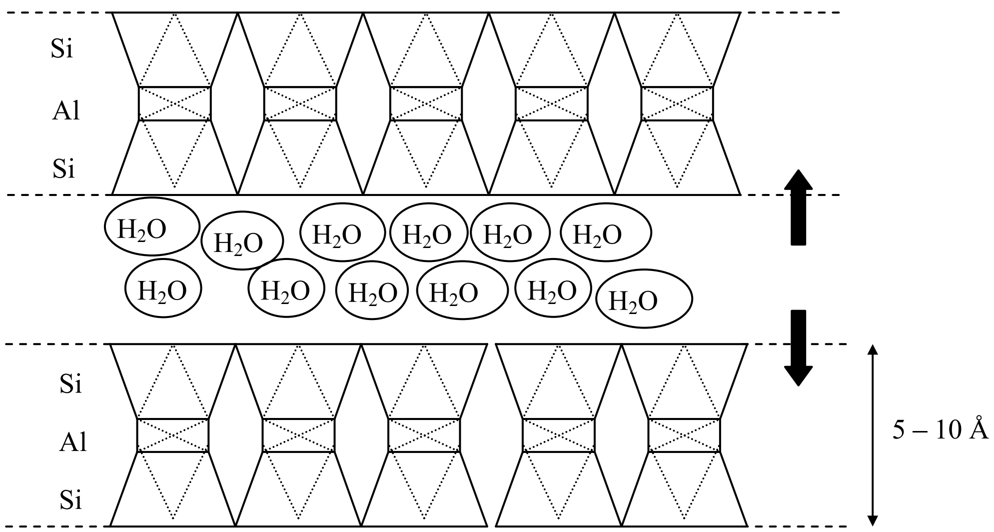

Figure 5. A diagram showing the intercalation of water molecules in the inter-plane space of clay smectites.

The expansive characteristics of smectites are affected by the nature of adsorbed ions and molecules. Smectite increases its plane spacing as a result of the loss of adsorbed cations.

Types of soil swelling

When a dry soil wets, during the first stage it undergoes three dimensional (3-D) volumetric expansions, because its desiccation cracks are still opened (Figure 6). In a second stage, after desiccation cracks were closed, soil volumetric expansion is only 1-D, causing the rising of soil level (Figure 7).

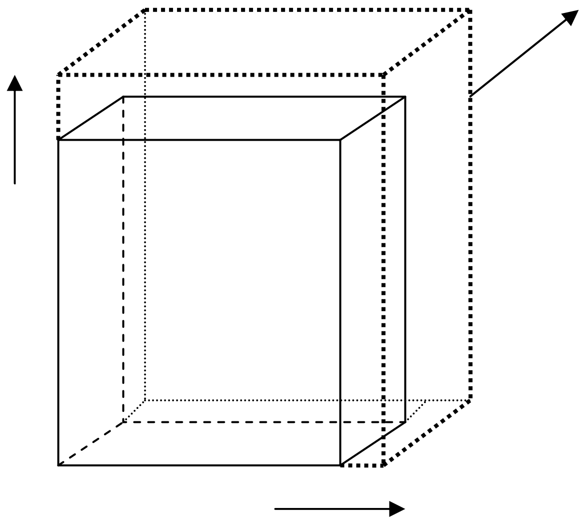

Figure 6. Schematic diagram of 3-D soil swelling

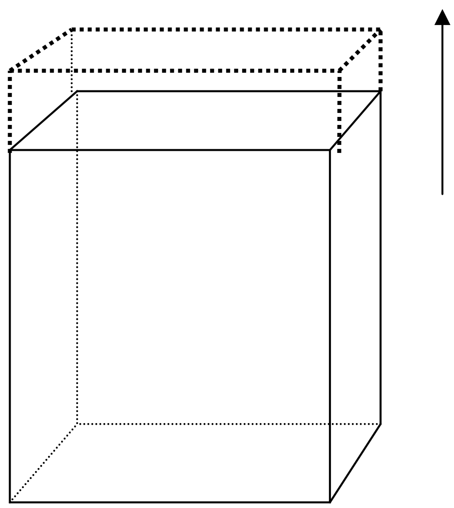

Figure 7. Schematic diagram of 1-D soil swelling

Consequences of soil swelling

Soil volumetric changes may cause both unfavorable and favorable effects on human activities. Unfavorable effects are the destruction of buildings, roads and pipelines in uncropped soils, and the leaching of fertilizers and chemicals below the root zone through desiccation cracks (by pass flow). In these soils horizontal cracks break capillary flux of water. On the other hand, swelling clays can be used to seal landfills storing hazardous wastes. This sealing avoids the downward migration of contaminants to groundwater. In cropped soils, the development of a dense pattern of cracks on drying improves water drainage and soil aeration, and decreases surface runoff in sloped areas. Soil cracking is closely related to the recovery of porosity damages by compaction. For a complete revision of these topics, the lecture of a review by A. R. Dexter (1988) is recommended. Here in, a conceptual model describing the sequence of paths leading to the development of desiccation cracks is provided (Figure 8). Tensile stresses are developed on drying, which to the creation of primary, secondary and tertiary cracks. The cracks are, at the same time, future void spaces, and represent the walls of the future aggregates. This sequence of paths is believed to recover soil porosity in a previously compacted soil layer.

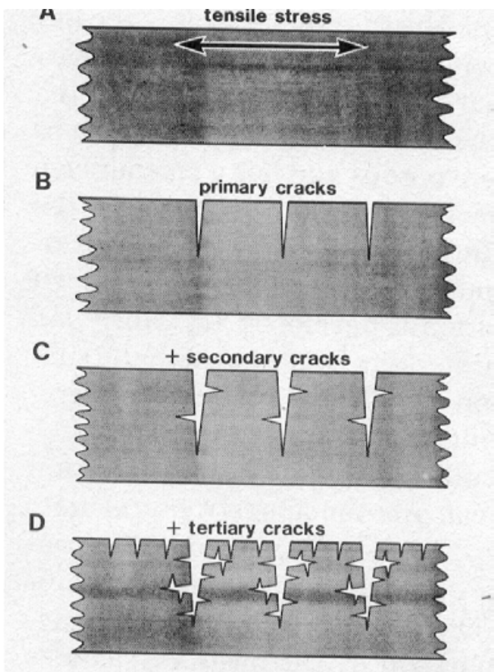

Figure 8. Conceptual model describing the development of primary, secondary and tertiary cracks, resulting from the build up of tensile stresses on drying (taken from Dexter 1988).

Methods for assessing soil swell-shrink potential

a) Coefficient of linear extensibility, COLE

It characterizes the variation of soil volume from 1/3 atm water retention (i.e. field capacity) to oven dry conditions:

$$COLE = (\nu_{1/3\ atm} - \nu_{dry})^{1/3} - 1 \qquad [2]$$

where $\nu_{1/3\ atm}$ is the soil volume at 1/3 atm water retention and ν_{dry} the soil volume at oven dry conditions. According to their COLE, a range of soil swell-shrink potential can be distinguished:

Soil swell – shrink potential ....:.....	COLE
Low	< 0.03
Moderate	0.03 – 0.06
High	0.06 – 0.09
Very high	> 0.09

The COLE index was found to be closely related to a number of soil variables (Parker et al. 1982). The higher determination coefficients correspond to the contents of total and swelling clays.

Independent variables	R^2
Clay < 2 µm	0.87***
Clay 2 - 0.2 µm	0.41**
Clay < 0.2 µm	0.43**
Smectites < 0.2 µm	0.61***
Interstratified swelling clay < 0.2 µm	0.2
Swelling clay < 0.2 µm	0.91***
Porosity	0.33*
organic C	0.08
Sodium Adsorption Ratio	0.01

b) The shrinkage characteristic or shrinkage curve (Mc Garry and Daniells 1987)

Each soil has a characteristic water retention curve, which relates its water content to the energy at which water is retained by the solid phase (soil matric potential). Likewise, swelling soils may be also characterized by its shrinkage curve. This shows the variation of soil specific volume, ν, with water content, θ, during the air – drying of water saturated natural clods.

To construct a shrinkage curve, the volume of natural soil clods must be determined by hydrostatic up thrust in a non polar liquid (kerosene) during air drying (Figure 9). The corresponding water content is also measured at different times of drying. Another option is to coat the clods with SARAN resin, and then, submerge them in water (Coughlan et al. 1991; Mc Garry and Daniells 1987; Mc Garry and Malafant 1987).

In a shrinkage curve the inverse of bulk density (i.e. soil specific volume, ν) is plotted to the volumetric water content θ of the soil (Figure 10). In this graphic two theoretical lines are depicted: a) the solid phase line (from the converse of soil particle density) that represents the lowest soil volume of a soil having zero pore space; and b) the 1:1 saturation line that represents soil swelling with zero air within pore space.

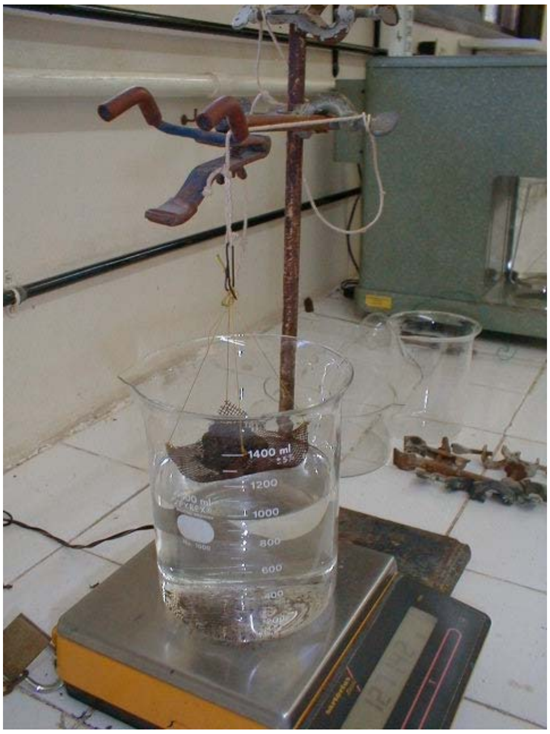

Figure 9. Experimental device to measure the volume of natural clods, by hydrostatic up thrust in a non polar liquid (kerosene)

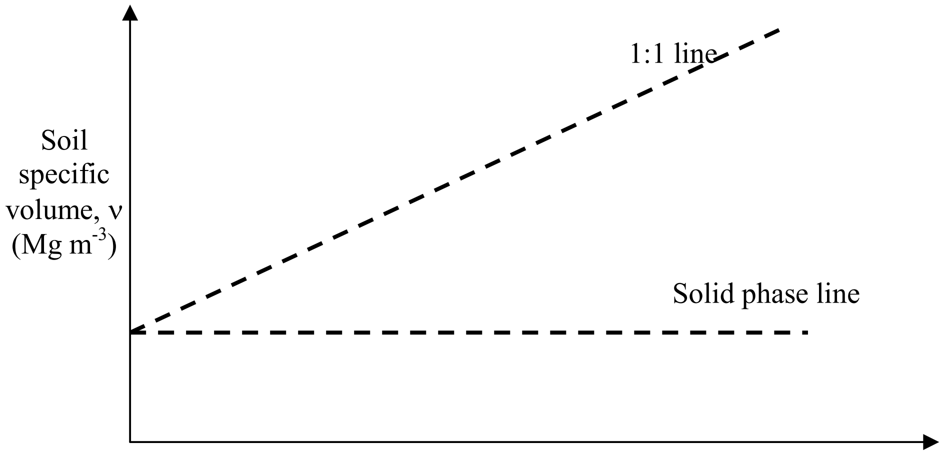

Figure 10. Initial plot to construct a soil shrinkage curve

After introducing $\nu - \theta$ pairs of data, straight lines can be fitted. This allows the identification of different shrinkage zones (Figure 11). Normal shrinkage ($B \rightarrow A$) is characterised by equivalent decreases in both ν and θ on drying, and thus, no air enters into soil pores (Coughlan et al., 1991; Mc Garry and Daniells, 1987). In the drier range of the θ variation, soil ν decreases during drying are lower or even null. Residual shrinkage ($A \rightarrow \alpha$) allows air entrance into soil pores, and hence the creation of air-filled porosity. Swelling soils are considered to have normal, or equivalent ν and θ variations throughout their water variation range. Moderately swelling soils, in turn, develop residual shrinkage during the drier range of soil moisture variation. This allows air entry to soil pore space, and the process is also recognized as irreversible shrinkage. The location of the air entry point θ_A is considered a index of soil quality in swelling soils, the higher θ_A, the better the soil aeration (Coughlan et al. 1991).

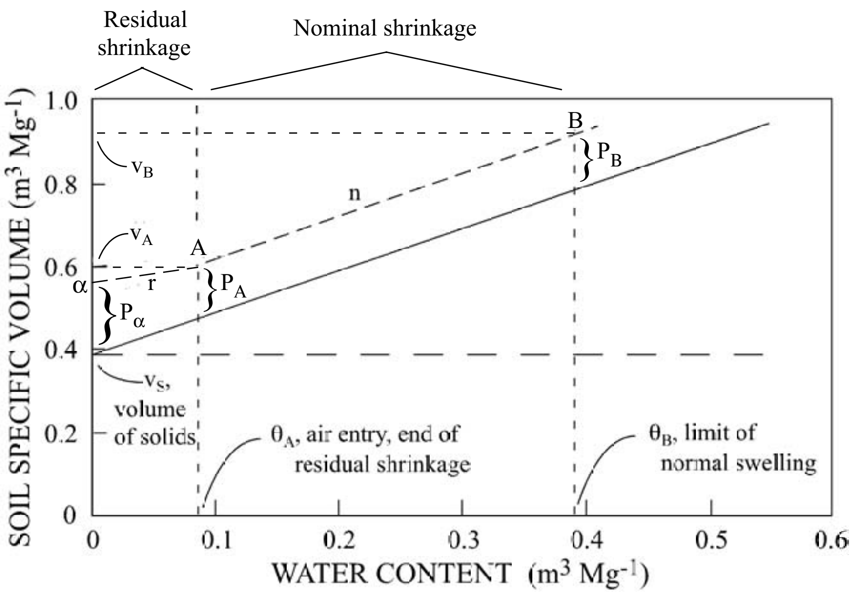

Figure 11. Theoretical shrinkage curve of a swelling soil.

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

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 $\rightarrow$ A (normal shrinkage)
r	slope of the line A $\rightarrow$ 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
θ_B-θ_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

Mc Garry and Daniells (1987) derived several indices and related variables from the shrink data of natural soil clods (Figure 11; Table 1). These are derived from the mathematical expression of two or three straight lines, fitted to the data. The figure shows the different soil shrinkage lines and indices of interest. We applied this approach to study soil volumetric variations in the Pampean soils of Argentina (Figure 12).

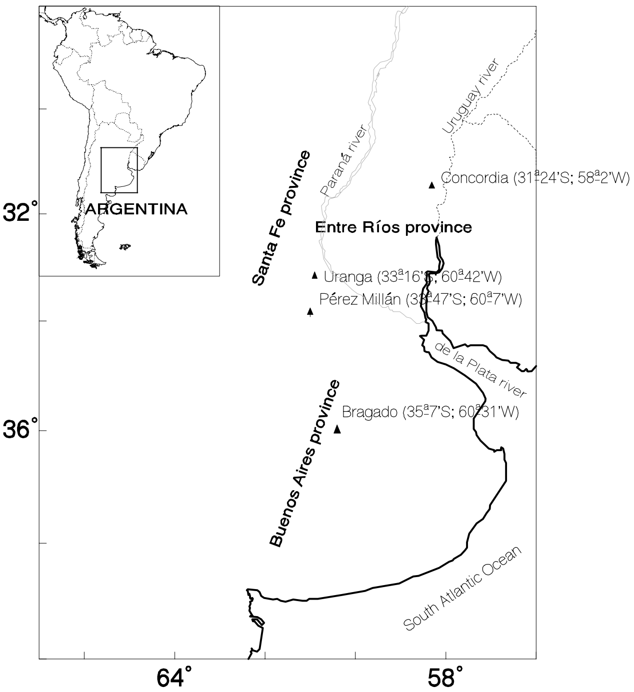

Figure 12. Geographical location of the main Argentine cropland area. Vertisols are highly conspicuous in Entre Ríos province, while silty loams covered thousand hectares in Santa Fe and Buenos Aires provinces.

a) Shrinkage characteristic of pampean silty clay loams affected by water erosion (Barbosa et al., 1999)

Silty loams (Argillic Phaeozems) are highly conspicuous in the north of the Pampean region. These soils are affected –to a different degree- by degradation, which can be classified in moderate and severe. Figure 13 graphically describes how degradation changed soil properties in the moderate and severe levels. Because of their high content of fine silt (2-20 μm), these soils have low structural regeneration capacity after degradation. We hypothesized whether this could be improved, or not, by the enrichment of topsoil with swelling clays. This situation can be found in severely degraded soils, in which the shallow A horizon was previously mixed with the below lying B horizon.

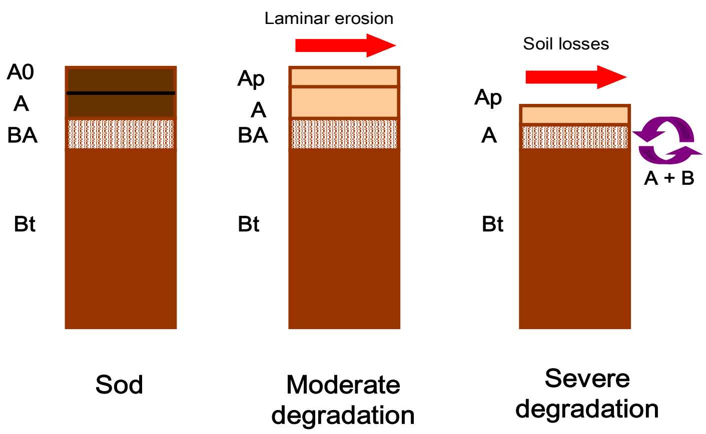

Figure 13. Idealization of soil profiles in non degraded (sod), moderately and severely degraded situations.

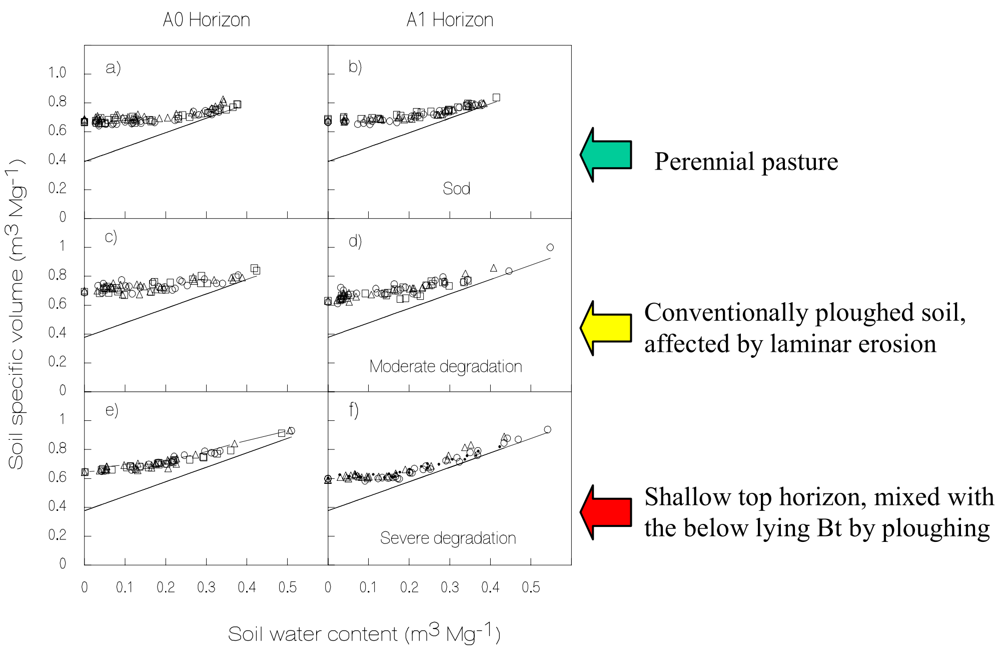

Figure 14. Soil shrinkage curves in the A0 and A1 horizons of a Peyrano silty clay loam (Argillic Phaeozem), under different degradation levels.

Soil shrinkage curves differed because of the different degradation levels (Figure 14). At first sight it becomes evident the wider volumetric variation range of the severely degraded soils. Soil volume at zero water content, α, and the air entry point θ_A showed no significant differences between the sod and moderately degraded soils, and were significantly lower in the severely degraded soil (Figure 15a). The slope, n, increased significantly from the sod to the severely degraded soil. The same happened with the normalcy range (Figures 15c and d). The severely degraded soil reached significantly higher volume, ν_B, and water content θ_B when swollen at maximum.

It can be concluded that clay enrichment (severe degradation) accentuated soil swelling (> ν_B and θ_B and normalcy range), but did not improve air filled porosity. Soil horizons mixture can not be recommended to the farmers, as a practice suitable to improve topsoil structure in Pampean silty loams.

b) Shrinkage characteristic of natric soils in the Flooding Pampa (Taboada et al., 2001)

In the flooding Pampa there are different kinds of Solonetzes, that are periodically flooded. The region is characterized by water table rises and surface ponding during winter-spring periods. Figure 16 (a through d) shows soil specific volume – water content relations in two different Solonetzes of the region. It can be observed that the fitted straight lines departed from the 1:1 line, showing air – filled porosity increases as soil wets.

The soils have no definite expansible clay mineralogy. Water table rises and surface ponding promote the build up of trapped air pressures in top horizons. This shows abnormal soil swelling caused by air entrapment.

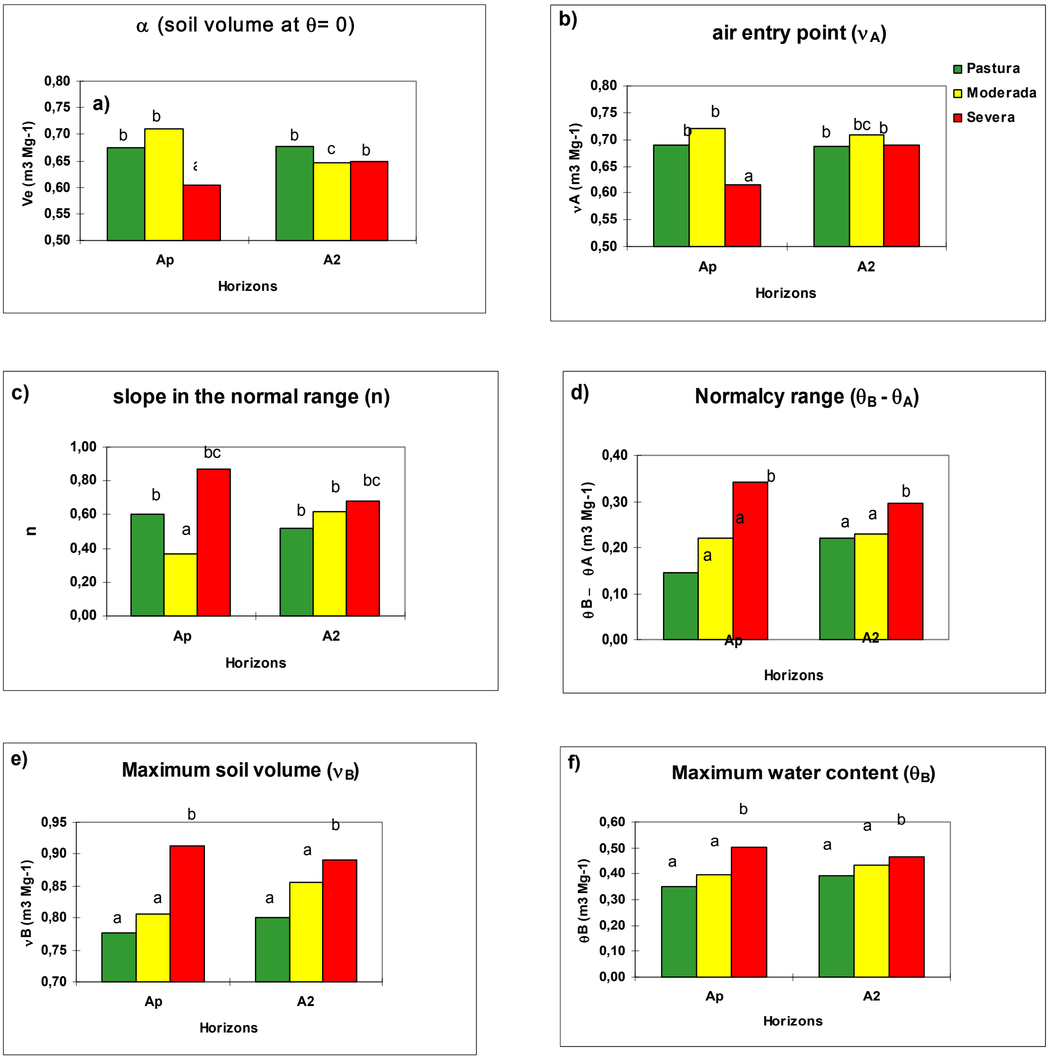

Figure 15. a) soil volume at zero water content, α; and b) air entry point θ_A in the sod, and moderately and severely degraded soils. c) slope in the normal range, n, and d) the normalcy range, θ_B - θ_A, in the sod, and moderately and severely degraded soils. e) maximum soil volume, v_B, and d) maximum water content, θ_B, in the sod, and moderately and severely degraded soils.

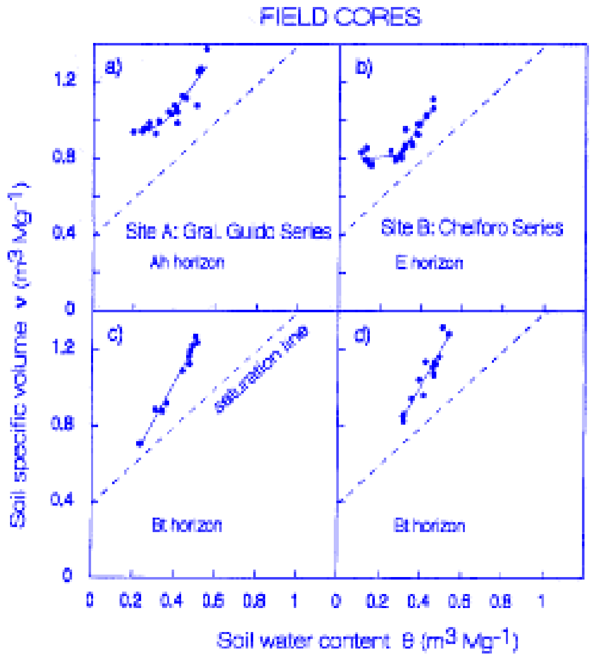

Figure 16. Soil specific volume, ν, - water content relationships from repeated core sampling of surface (a, b) and Bt (c, d) horizons of two Solonetzes.

In the environmental conditions of the flooding Pampa of Argentina, trapped air is responsible for most of the swelling of soils having little expansible mineralogy of clays. Results show that trapped may an important soil swelling factor in soils.

Recommended bibliography

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