Soil Structural Behaviour of Flooded Soils

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The objectives of this presentation are to:

- identify factors determining of the structural behaviour of flooded soils, as compared to those acting in upland soils;
- analyse the influence of reductive processes on aggregate stabilising agents;
- discuss mechanisms of structural deterioration and recovery during the flooding-drying cycle, on the basis of a case study: cattle trampling effects in the flooding Pampa of Argentina.

Flooded soils: where do they occur?

Flooded soils, now known as Hydric soils, are characteristic of wetlands and irrigated fields cropped to rice (paddy soils). In them, water covers the soil, or is present either at or near the surface of the soil all year or for varying periods of time during the year. Hydric soils belong to different taxa of the FAO-UNESCO Soil Map (2000). Figure 1 (a, b, c) shows the geographical distribution of Fluvisols, Planosols and Gleysols in the World.

As can be observed, they are widespread distributed in the globe. The generation of redoximorphic features is due to different causes in each of them. Fluvisols are covered part of the year by surface water from river overflows; Planosols are soils having an impervious Bt horizon, supporting perched water during short periods; and Gleysols are soils affected by stagnant water tables during long periods.

Key factors determining the structural behavior of flooded soils

The structural behavior of flooded soils received in general terms little attention by published literature. This behavior is affected by these characteristics:

a) the development of anaerobiosis and reductive processes, and whether they affect, or ntr, soil organic matter (SOM);

b) the quality of flooding water, as strongly depending on its origin (where does flooding water come from?);

c) the response of soil to ponding – drying cycles (when soil is susceptible to structural damage? and how fast soil damages are recovered?).

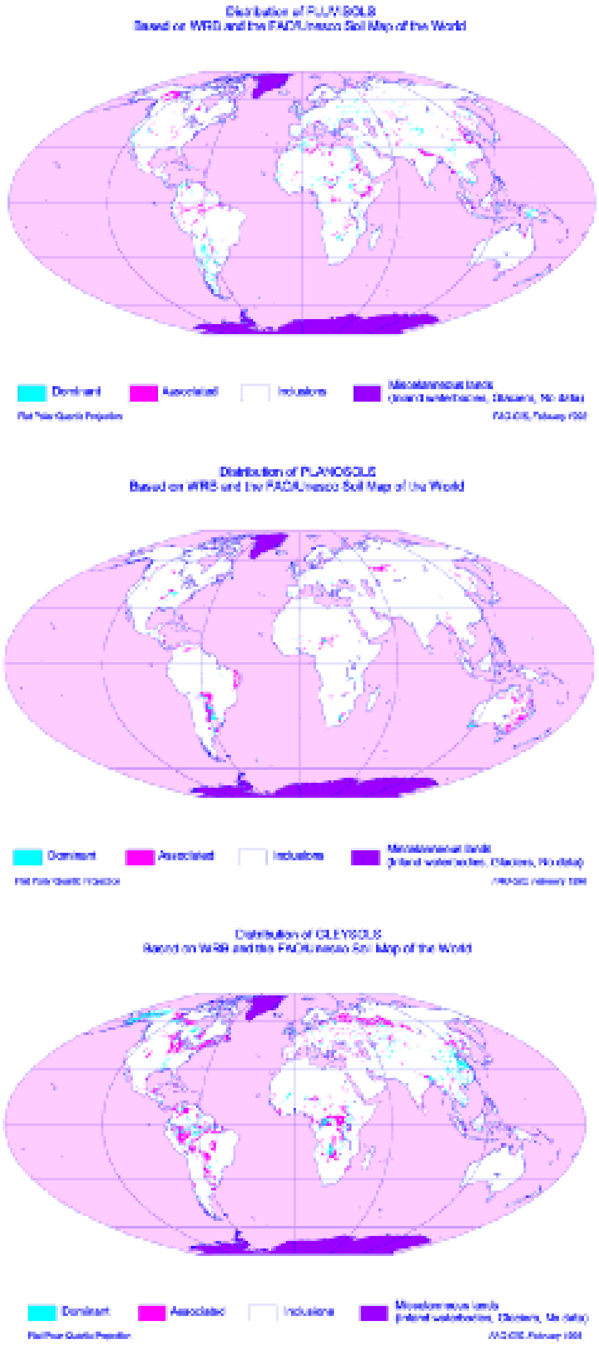


Figure 1. Geographical distribution of Fluvisols (a), Planosols (b) and Gleysols (c) in the World (FAO-UNESCO 2000)

Reductive processes in flooded soils

Hydric soil identification is normally done by looking for these redoximorphic features:

- Grey colours (chromas < 2 in Munsell Soil Color Chart)
- Red mottles
- Concretions of Fe-Mn
- Sesquioxidic glebules
- Gley horizons with yellow and olivaceous colours (hues < 10).

There is a sequence of reductive processes in flooded soils, as a function of the decrease in soil redox potential (Eh) and the prevailing redox couple taking part in each stage of reduction (Patrick and Mahapatra, 1968). This sequence is described in Table 1.

Table 1. Sequence of reductive processes (after Patrick and Mahapatra, 1968)

range of Eh 7 (mV)	redox condition
> 600	highly oxidated
600 to 300	oxidated
300 to 100	moderately reduced
100 to - 100	reduced
< - 100	highly reduced

Oxidated soils (non flooded) have most time high Eh values (> 300 mV), and in them oxygen (O_2) is the main acceptor of electrons in soil respiration processes. In periods when O_2 disappears from soil atmosphere, typically when soil is flooded, ponded or waterlogged, the electron donned by soil organic matter are then accepted by soil nitrates (NO_3^-) that, in this way, are reduced to molecular nitrogen (N_2) and nitrous oxides (NO_x). This process is known as denitrification, it means a loss of nitrogen evolving to the atmosphere. Soil nitrates disappear only in some days, thus allowing that other redox couples take place. They are those composed by FeIII – FeII, and MnIV, III – MnII compounds. Mineral soils usually have high contents of several iron and manganese oxides and hydroxides, so that Eh values seldom decrease below about -100 mV in seasonally flooded soils. Only those soils that remain submerged for long periods, such as some estuarine soils and permanent ponds can reach high reduction. In them Eh values may reach highly negative values, and as a result, sulphide and methane gases are emitted from these soils.

Due to their low mineralization rate under reduced conditions, flooded soils tend to accumulate high organic carbon contents. These high organic matter contents have strong influence on soil structural behavior.

Figure 2 shows results obtained by Lavado and Taboada (1986) in the flooding Pampa of Argentina. We measured water table depth and topsoil redox potential during about three years, during which s the soil was ponded during winter – spring periods. The topsoil was most time under moderately - reduced conditions, according to its condition of grassland soil. Only during ponding periods became the topsoil highly reduced.

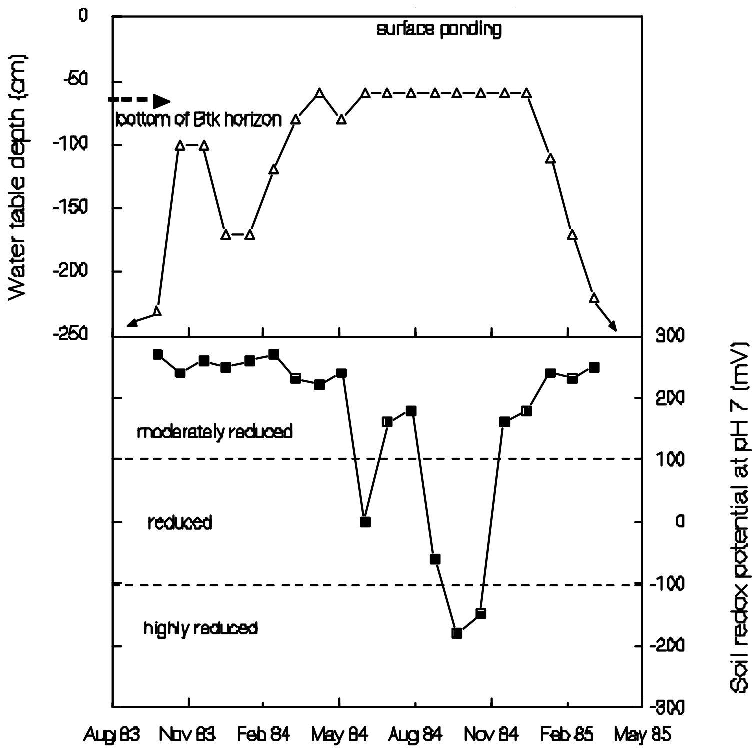


Figure 2. Water table depth and topsoil redox potential in a Solontez of the flooding Pampa of Argentina (after Taboada and Lavado, 1986).

Quality of flooding water

Soil profile characteristics determine whether groundwater reaches soil surface, or not. The evolution of soil structure after flooding mainly depends on the quality of flooding water (e.g. salinity, sodicity, type of sodium salt, etc.) (after Lavado and Taboada, 1988). It is important to determine the origin of flooding water, which in about 90 % of cases comes from groundwater. The diagram in Figure 3 shows the possible consequences of different kind of water qualities on soil structure. Soil ponding or flooding by fresh water does not cause severe consequences; only those related to the loss of soil bearing capacity. In change, soil flooding by salty or brackish water may lead to irreversible consequences, such as those caused by alkali excesses on soil structure.

Whether the soil will be ponded by fresh or salty water it will depend on soil profile characteristics. Figure 4 illustrates two cases. Those soils not having a tough Bt horizon allow free down- and upward water movements throughout the profile. So, in them groundwater rises may reach the topsoil, causing eventually (if groundwater has high salt contents) saline deposits in surface horizons. This situation mainly concerns to most Fluvisols.

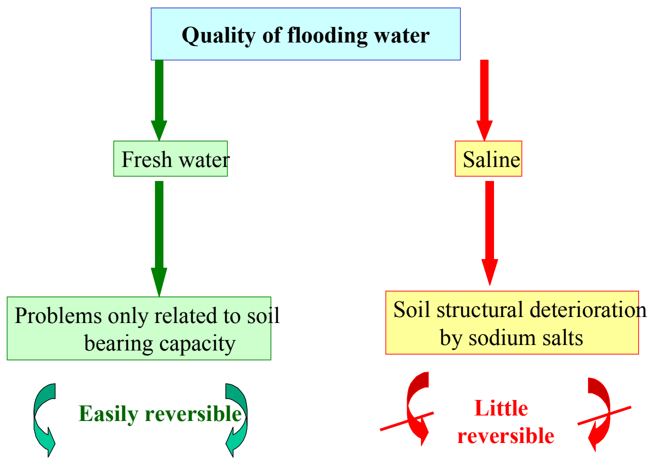
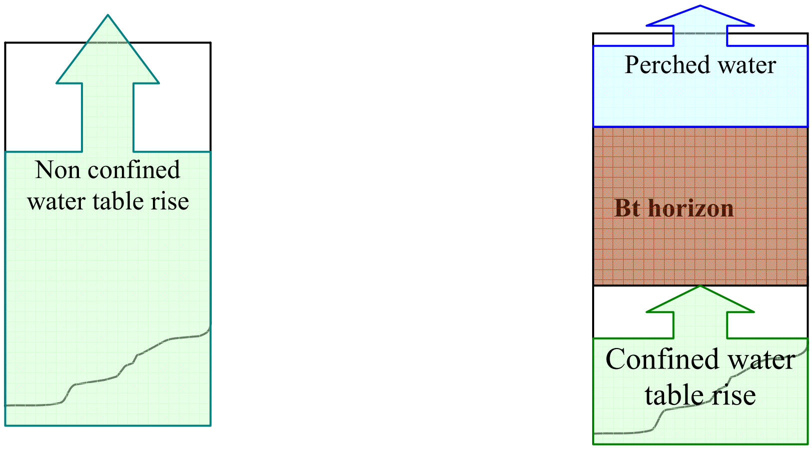


Figure 3. Schematic diagram showing the consequences of flooding water quality on soil structure



Soils without Bt horizon:
free groundwater rise

Soils with a tough Bt horizon:
Confined groundwater rise and
surficial accumulation of rain water

Figure 4. Schematic diagram describing unconfined and confined groundwater rises in soils not having and having a tough Bt horizon.

Figure 5 shows the profile of Solonetz of the flooding Pampa of Argentina. It can be observed a columnar Bt horizon, above which a perched water table is seasonally accumulated. In these kind of soils, floods are largely caused by the accumulation of rain water from the perched water table. Calcium carbonates are precipitated at the bottom the Bt horizon, showing the zone of maximum groundwater rise.

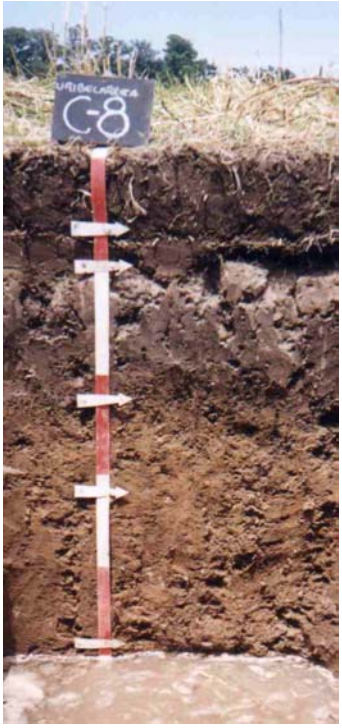


Figure 5. Mollic Solonetz in the northen flooding Pampa of Argentina, having a tough natric horizon with columnar structure. Groundwater can be observed at the bottom.

The case of fresh water flooding: when soil is susceptible to structural damage?

In these soils ponding periods correspond to losses in soil bearing capacity. The "Proctor Curve" constructed from a compactibility test can predict the probability of bulk density increases caused by impact stresses upon soil (Figure 6). This curve indicates that a given soil reaches a maximum density at a critic water content. This critic water content is always lower than saturation.

According to the prediction provided by a Proctor test, a given soil will be resistant to support structural damages when dry. At this condition it will have high bearing capacity, and low susceptibility to structural damage by trampling or agricultural traffic. When soil is wet, in change, its bearing capacity is low, and it becomes prone to undergo structural damage. We tested the case of trampling damages by cattle trampling in the flooding Pampa of Argentina, in which the soils are periodically flooded as shows the picture in Figure 7.

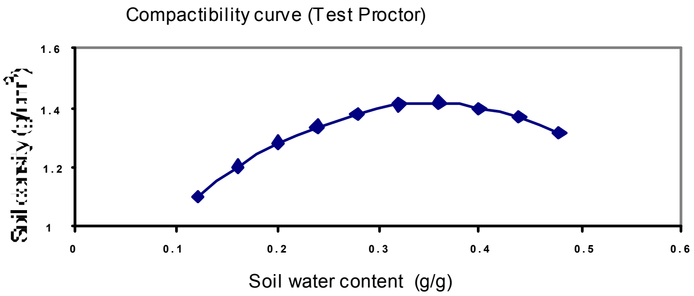
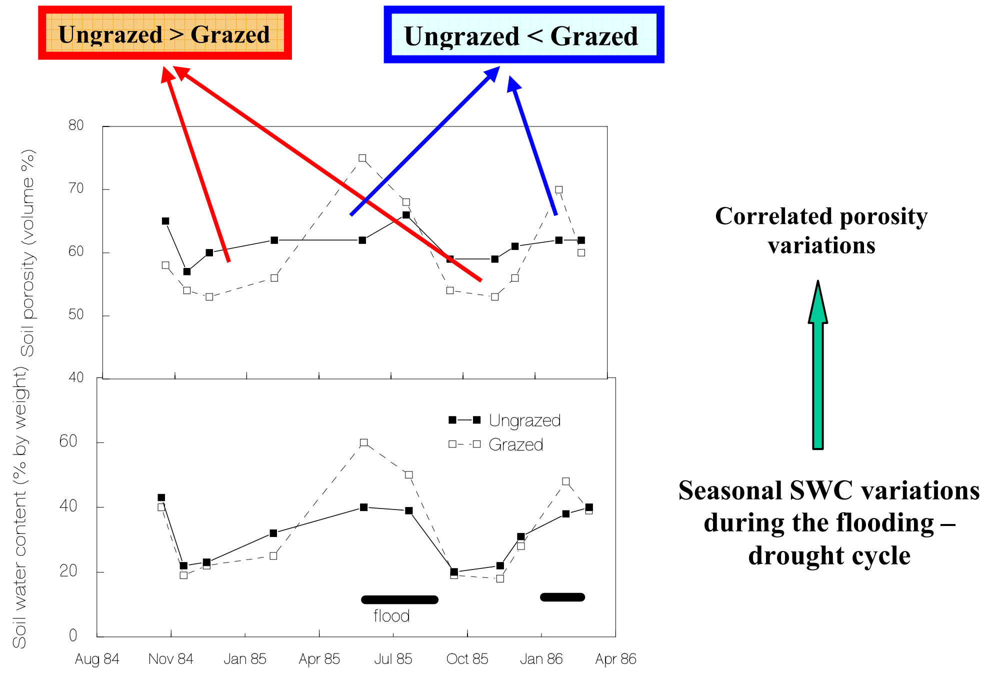


Figure 6. Theoretical soil density – water content relation obtained from a compactibility test (Proctor test).

Figure 7**.** Landscape view of flooding in the flooding Pampa of Argentina.

In this region structural damage by poaching when a flooded soil is trampled by large hervibores is expected. Poaching is caused by the repeated impact of animal hooves, which weakens topsoil structure. This results in large and massive soil clods, which become very hard when dry. What did we find when studied cattle trampling effects in the center of the flooding Pampa of Argentina?



(after Taboada and Lavado 1993)

Figure 8. Variations of soil water content and total porosity in a Solonetz of the flooding Pampa of Argentina, in grazed and ungrazed exclosure situations.

Figure 8 shows the variation soil water content, which followed as expected the seasonal ponding-drying cycle. Total soil porosity followed the variations in water content, because of the occurrence of swelling and shrinking. Trampling effects were investigated by comparing grazed to ungrazed situation. The latter corresponded to a 4 ha exclosere deferred from grazing for several years. In the figure, it can be observed that soil porosity was significantly higher in ungrazed than in grazed situations in summer periods, when soil was somewhat dry. The opposite occurred during winter- spring periods, showing the recovery of porosity damages during floods. Results show that structural damages by poaching did not occur under our study conditions (continuous grazing by about 1 stock per ha).

Cattle trampling effects are expected to affect mainly the larger soil pores. Figure 9 shows the response of these pores in summer and winter. In agreement with the effects on total porosity, trampling caused the destruction of topsoil pores > 60 µm, in summer when soil is dry. This damage was fastly recovered some months later, during winter ponding when soil macroporosity was higher under grazing.

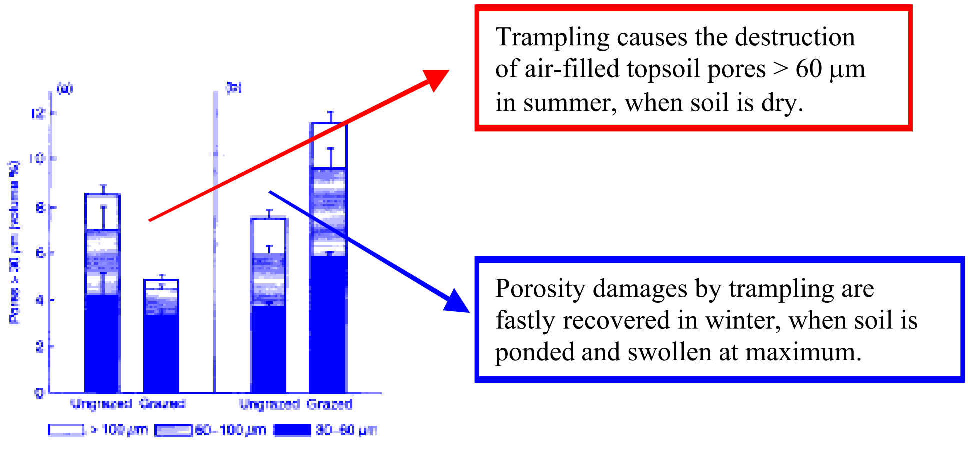


Figure 9. Soil macroporosity in the 30 – 60 µm, 60 – 100 µm, and > 100 µm pore size ranges in summer and winter.

Aggregate stability variations followed the same pattern of soil porosity (Figure 10). They showed higher stability values in the ungrazed exclosure during summer, and stability recoveries during winter, when soil is flooded.

The periods when trampling affects topsoil porosity and aggregate stability agree well. They are in summer when soil is dry. The same happens with the periods for porosity and stability recovery. They are in winter when the soil is flooded. This structural behavior is opposite to expectation, as trampling did not cause structural damage by poaching. We propose a conceptual model showing the process of soil structural destabilisation when the soil dries, and the process of structural recovery when the soil wets (Taboada et al. 1999). This conceptual model is depicted in Figure 11.

The conceptual model that postulates decreases in structural stability resulting from crushing air-filled pores by cattle hooves. This yields smaller water-stable aggregates, as shown by the higher proportion of aggregates < 0.3 mm usually found in the soil of the grazed area compared to the soil in the enclosure area. Only at low water contents was the structure of the topsoil destabilized by grazing. The recovery of structural stability began in the fall and was completed in the winter, when the soil was ponded. The structural recovery results from swelling, when the smaller aggregates created by trampling of dry soil are bound again into larger structural units.

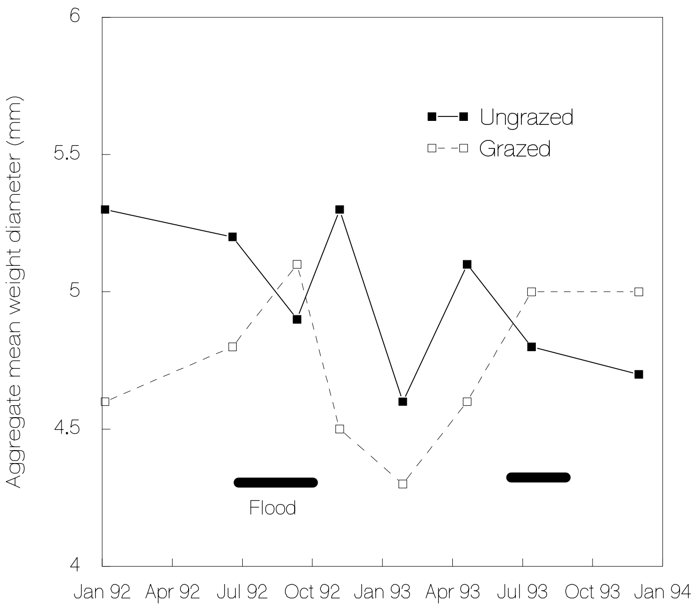


Figure 10. Aggregate stability variations in ungrazed and grazed situation in the flooding Pampa of Argentina.

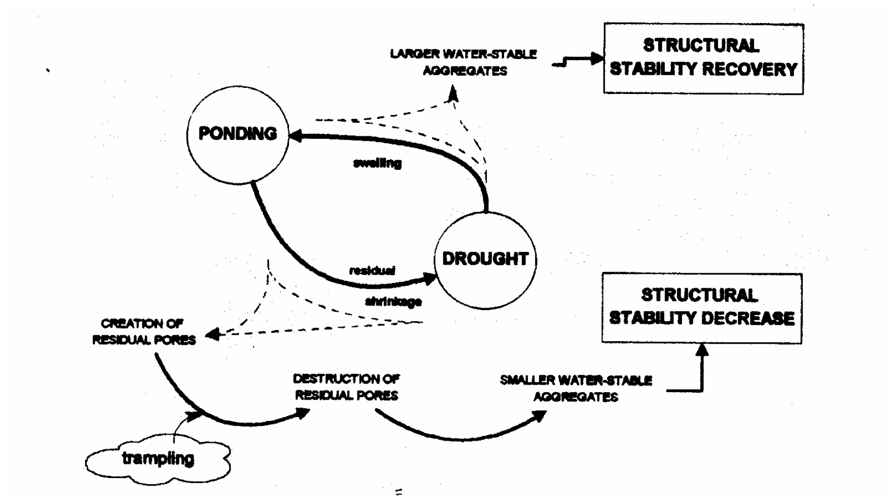


Figure 11. Conceptual model showing the variations in soil aggregate stability in the flooding Pampa of Argentina.

Upland soils tend to decrease their stability when sampled wet, and to increase it when sampled dry. This stability regime is commonly known as the “antecedent soil moisture content effect”, and it depends on the build up of soil cohesion forces. The studied flooded soils showed an opposed response to the antecedent soil moisture effect. It can be concluded that in flooded soils their structural behavior is mainly determined by their volumetric response to the ponding – drying cycle.

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