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Moisture and salinity profiles in the French Atlantic coastal marshes and consequences on plant available water

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ABSTRACT

Study region: French Atlantic coastal marshlands.
Study focus: These coastal marshes have been reclaimed from the sea by successive polderizations since the Middle Ages. The soils have been formed by desiccation, consolidation and maturation of clay-dominated sediments initially saturated by seawater. Since the 1970′s the extensive cultivation of grain was accompanied by widespread drainage in order to deepen the groundwater level and increase the thickness of surface leaching by rainfall. Gravimetric water and salinity profiles were recorded in an undrained grassland and a drained cornfield profiles during the period of corn plant growing from July to September 2013. The simple available water capacity (AWC) calculation from surface parameters were compared to vertical profiles of plant available water (PAW). The limit between the vadose and saturated zones was determined by comparison between the shrinkage and compaction pathways of the clay matrix. Patterns of the PAW profiles were calculated and modeled following simple second-degree polynomial equations.
New hydrological insights for the region: The results demonstrate the PAW evolution at successive depths compared to deepening evapotranspiration drying fronts and ascending capillarity rise. Based on soil water contents measured at 10 cm and/or 20 cm depths, the modeled PAW profiles are found sufficiently realistic to be used as an efficient tool to aid crop farming in these territories governed by the superimposed water and salt stresses.

1. Introduction

The coastal marshlands have been generally reclaimed from primary fluvio-marine sediments. They result from hydraulic managements and/or polderization that may date from the Middle Ages. Historically these hydraulic managements were built for reasons of sanitation, breeding and farming. For the intensive grain crops the slow drying caused by land reclamation

Abbreviations: AWC, available water capacity equivalent to the difference between the water content at wilting point and water content of retention capacity (field capacity); AWC_{ref}, available water capacity calculated from soil texture used as reference in the work; PAW, plant available water calculated taking into account the real water content of soil for the different dates; PE and ETm, potential and maximum evapotranspiration; RR, rainfall; W, gravimetric water content; Ws, Wp, Wl, shrinkage plasticity and liquidity limits; W_{fc}, field capacity; W_{wp}, wilting point; $EC_{1/5}$, 1/5 electrical conductivity; Kc, crop coefficients; Ks, hydraulic conductivities at saturation; AEP, air entry point; GWET, groundwater evapotranspiration; VZET, vadose zone evapotranspiration.

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was recently improved by drainage. The primary sediments were generally saturated by salt water, thus, the current water table and deepening desiccation front cause synchronous evolutions of the water content and salinity profiles. In these shallow groundwater regions the capillary rise may have dominant roles in the mechanisms of plant-soil interaction, such as soil water flux, crop rooting and water salinity (Ayars et al., 2001, 2006a, 2006b).The shallow groundwater may have a positive role on plant growth via water supply and/or a negative role via waterlogging or salinization (Nosetto et al., 2009). Crops also influence the water and salinity profiles, and consequently the groundwater level via the PE or ETm balances (Fan et al., 2014).

One can explain that plant growth and crop yields are partly governed by the soil AWC and secondly by the water content and associated PAW profiles with soil depth. AWC is commonly calculated from the soil texture (clay/silt ratio) and/or from the difference between the water content at field capacity and at wilting point (Bruand et al., 1996; Rawls et al., 1982; Mathieu and Pieltain, 1998; Saxton and Rawl, 2006). Such calculated AWC is a basic parameter characteristic of the potential (maximum) of water retention by the soil which can be used as a reference but which is independent of weather conditions and the water consumption of plants. This AWC may be upgraded by taking into account the rainfall (RR), the potential of evapotranspiration (PE) and the crop coefficient (Kc) in the AWC_{PE} or AWC_{ETm} calculations for grassland and grain crops, respectively. In fact, plant growth and crop yields are mainly governed by soil moisture profiles and the evolution of the PAW profile throughout the seasons. Firstly, the PAW changes according to seasonal variations of the water profiles resulting from the competition between the rainfall and PE or ETm. Secondly, in shallow groundwater fields the PAW is largely supplied by the groundwater capillary rise. Numerous simulations of water flux in saturated and vadose zones have been conducted since the 2000s' (Guber et al., 2009). The difficulties of modeling are in part due to difficulties in the measurement of the water retention and hydraulic conductivity of clayey soils. They are also due to the nonlinear hydraulic properties of the upper vadose zone. The amount of parameters to be considered led to the development of a multi-model prediction in 1969 (Bates and Granger, 1969). The pedotransfer functions have largely been developed but the challenge is to fit the models to the different fields, crops and soils. For different studied fields, the question is: how to adapt a multi-model to the *in situ* available parameters, and can a simple model be realistic enough for crop farming?

Generally, the soils of the coastal marshlands have two dominant features:

- a silty-to-clay dominated texture, inherited from the primary sediments and responsible for drastic properties of shrinkage
- and *in situ* shallow groundwater table, characterized by medium to high salinity.

The clay dominated nature of the soils impacts their hydro-mechanical properties and water fluxes through the changing micro-to-meso structure of the clay matrix from the surface to the depth (Archer and Smith, 1972; Kern, 1995a,b; Saxton and Rawls, 2006; Bernard et al., 2007; Bernard-Ubertosi et al., 2009; Gallier et al., 2012). Indeed these clayey soils present important shrinkage/swelling properties depending on water content. Furthermore, because of close mineralogy and texture they always present the same gravimetric water contents (W) at the characteristics shrinkage (Ws), plasticity (Wp) and liquidity (Wl) limits. From the surface to the depth, the gravimetric water content increases due to the presence of a shallow water table and capillary rise. As a result, according to the progressive increase of W with depth from the surface to the depth the clay matrix presents solid state pathways from shrinkage limit (Ws) to plasticity limit (Wp) and plastic state pathways from Wp to liquidity limit (Wl) (Fig. 1a). The depth at which these changes (Ws to Wp to Wl) occur is an important parameter for the hydromechanical behavior of the soil and the associated water content profiles. Decreasing the size of micropores according to the desiccation/shrinkage phenomenon decreases the capillary rising rate but increases the height of capillary fringe (Fig. 1b). The shallow silty-clay aquifers suggest a large groundwater recharge by capillary rise in response to the evapotranspiration flux (Ayars et al., 2006a,b; Fan et al., 2014).

In parallel, regarding the capillary fringe, plant growth and rooting depth are also governed by the thickness of the vadose zone, groundwater saturated zone and water table level. In such clay dominated soils and shallow salty groundwater, the competition between evapotranspiration and groundwater supply governs the water content profiles and the hydric stress plus salt stress combine. The kinetics of the water profile evolutions are partly governed by the associated clay matrix micro-to-meso structure (shrinkage/swelling) and water table level. During the last twenty years, many authors have used pedotransfer functions at the scale of soil profiles in order to link the prevailing weather conditions, the rooting depths and the crop coefficients (Nosetto et al., 2009; Guber et al., 2009; Bastet et al., 1998; Bruand et al., 2002, 2004; Morvan et al., 2004; Bruand and Coquet, 2005; Choisnel, 1992; Nyvall, 2002; Hong et al., 2013). In such shallow, silty-to-clay groundwater territories the question is also how to monitor the saturation front and consequently how to quantify groundwater evapotranspiration and vadose zone evapotranspiration (Ayars et al., 2006a,b; Shah et al., 2007). More recently, the definition of soil water availability has been broadly discussed regarding the transpiration demand and root development of plants (Couvreur et al., 2014). Thus, works on the soil water stress function suggest a "limited soil water availability" depending on plant potential transpiration rate and root water uptake evolution: i.e. hydrodynamics of the soil-plant system (Javaux et al., 2013). In fact, the root water uptake depends on both a three-dimensional root network and surrounding clay matrix hydraulic conductivity. Moreover, the mechanisms are also disturbed by heterogeneities at the root-soil interfaces. Root growth provokes the rearrangement of clay particles along the root surface through mechanical and desiccation stresses on the clay matrix. Such "compaction" of the clay matrix drastically decreases hydraulic conductivity (Gallier et al., 2012). In the vadose zone, the soil-root hydraulic resistance may be also impacted by air gaps at the soil-root interface (Carminati et al., 2009). In all cases the AWC, AWC_{PE} and AWC_{ETm} are calculated from the "surface conditions" only: i.e. weather including