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Hydrostructural Pedology, New Scientific Discipline Allowing for Physical Modelling of 'Green Water' Dynamics in the Soil-Plant-Atmosphere System

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Authors' contributions

This work was carried out in collaboration between all authors. Author EB designed the study, performed the theoretical work and physical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors HB and ATA managed the analytical means and methodology of the study. Authors RHM and ATA managed the manuscript corrections and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Using a new paradigm of soil characterization and modeling in agro environmental sciences, named hydrostructural pedology, we were able to show that the "green water" concept of agronomists corresponds exactly to the pedostructural water concept which was physically defined in this paradigm. The water in the pedostructure of soils is composed of two types of water, named micro and macro, nested one in the other. They are differentiated by their chemical potential related to their position in the pedostructure: inside primary aggregates or outside of them in the interpedal space. A fundamental physics of the pedostructural water could be developed within this new paradigm. Finally, the soil medium can now be considered as the location in which the free water (named also blue water), coming from surface (rainfall, irrigation, etc.) and going down by gravity through the macro pore space of the soil, is partially absorbed by the pedostructure, and becomes

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then the 'green water' of the soil. Soil green water is, in fact, the soil water reserve available to plant roots and subsequently transpired by the plants into the canopy. The soil-water model Kamel®, built according to this new paradigm, is the only model able to physically simulate the opposite dynamic cycles of these two kinds of water (blue and green) within the soil-plant-atmosphere system, their exchanges and equilibrium states according to time, at each depth of the pedon. Important implications about strategy of soil-water characterization, mapping and modeling are given for sustainable development and management of agricultural zones.

Keywords: Systemic approach of soil organizations; systemic soil water modeling; soil hydrostructural characterization; soil pedostructure; pedostructural water; soil green water; hydrostructural pedology laboratory; soil hydrostructural properties.

1. INTRODUCTION

Recently [1], the International Soil Reference and Information Center (ISRIC) defines three kinds of water: "From the perspective of crop production, rainwater may be split into green, blue and white components:

- *Green Water* is the water infiltrating into the soil, taken up by roots, used in photosynthesis and transpired by the crop;
- *White Water* is intercepted and directly evaporated by the crop canopy and the ground surface;
- *Blue Water* is made up from run-off to rivers and deep percolation to aquifers that finds its way to rivers indirectly."

The green water and blue water concepts were presented in 2006 by Falkenmark and Rockström [2] as a new paradigm for water resources planning and management.

The green water in eco- or agro-systems can certainly be compared to the blood in animals: an operative component of the system. The blue water, on the other hand, is free water flowing by gravity through the macro-porosity of the soil and without interaction to the passage other than that of being partially absorbed by the clayey plasma within the soil structure. However, although these concepts have been well known and used in agronomy for some fifteen years, no one has yet provided the material and conceptual means to measure and model the dynamics of these two components of water in the soil. Actually, a major issue in the existing soil-water modeling is the lack of having a quantitative modeling approach that considers the natural hierarchical organization of the soil medium (i.e. soil structure). Thus, these soil water models are not able to 1) differentiate the different kinds of water present and acting in the soil medium organization; (2) provide the representative parameters that characterize the soil structure and its hydraulic functioning (i.e. have hydrostructural "physical" parameters instead of empirical parameters that have no physical meaning); and they have not the ability (3) of coupling the biological and geochemical processes in soils with the hydrostructural behavior of the soil medium (i.e. quantitative understanding of the impact of agro-environmental practices on the soil behavior); and (4) of coupling and integrating results from the local scale of processes in the soil medium (primary peds and pedostructure) to the upper hierarchical scales in the natural environment system (field, soil mapping unit).

Face to this challenge, Braudeau and Mohtar [3] claimed that distinguishing different kinds of water within the soil matrix organization is impossible without a change in soil water physics paradigm that recognizes this matrix organization and its structure [3]. They proposed a new approach of the soil water physics wherein the REV concept of the soil medium is replaced by the *SREV concept* (Structural Representative Elementary Volume) that, contrary to the REV, take the soil structure and its hierarchical organization into consideration. A new paradigm of the soil description and modeling, named hydrostructural pedology [4,5,6], emerged from this approach, and the question to be asked now is whether the green water and blue water of the soil can be identified and quantified and whether their respective dynamics within the soil-plant-atmosphere system (called also 'critical zone') can also be modeled.

2. THEORY

2.1 The Hydrostructural Pedology Paradigm

The new paradigm proceeds from the application of the systemic approach to soil science [7]; it addresses not only the organization of soils in the landscape (soil mapping) but also, innovatively, the hierarchical internal organization of the "soil medium". The important first results were the establishment of the basic concepts of the new discipline, like pedostructure, primary peds, primary soil mapping unit (Fig. 1), and the concept of SREV coming from application of the systemic approach to soil organization. At the same time, a new set of descriptive variables was established to quantify the hierarchical organization of the soil, as depicted in Fig. 1, including the three nested levels of organization of the pedon.

The SREV variables are said “systemic” because they are defined according to the systemic approach, as opposed to “non-systemic” variables currently used in soil physics and defined according to the concept of REV. Thus, the new systemic paradigm imposes the exclusive use of this set of variables in all equations of the hydrostructural soil functioning, and these equations are valid for all types of soil [8].

2.2 The 4 Hydrostructural Functions of the Pedostructure

The pedostructure, then, is like the motor element of the soil. The only cause of swelling and shrinkage of the soil horizon is the pedostructure volume change according to the pedostructural water content. Thus, characterizing the hydro-structural behaviour of a soil horizon in the laboratory is to characterize the hydrostructural properties of its pedostructure, whatever the percentage of volume occupied by the latter on the horizon.

The use of the new hydro structural pedology paradigm allowed discovering the exact equations of state of the pedostructure that characterize the thermodynamic and hydrostructural equilibrium between the two types of pedostructural water (W_{mi} and W_{ma}, internal and external to primary peds in the pedostructure) [9]. This, in turn, led to the establishment of theoretical equations of the four pedostructural characteristic curves that fully represent the hydrostructural properties of soils [9,10] and [11]; these are:

- *The soil water retention curve*, $h = f\left(W_{ps}\right)$: the tension of the soil water expressed in suction pressure (hPa), function of the pedostructural water content $\left(W_{ps}\right)$ (in kg water/kg soil structure) [9,10].
- *The pedostructural shrinkage curve*, $\bar{V} = f\left(W_{ps}\right)$: Pedostructure specific volume (dm^3/kg) as function of the pedostructural water content [9].
- The pedostructural hydric conductivity curve, $k_{ps} = f\left(W_{ps}\right)$ (dm/s) as function of the pedostructural water content [11].
- *The pedostructural swelling curve*, $\bar{V} = f(t)$, which is the swelling with time of the pedostructure by absorbing free water [11].

These four curves are dependent on the thermodynamic interaction between the water molecules and the surface charges of soil particles, both organic and mineral, constituting

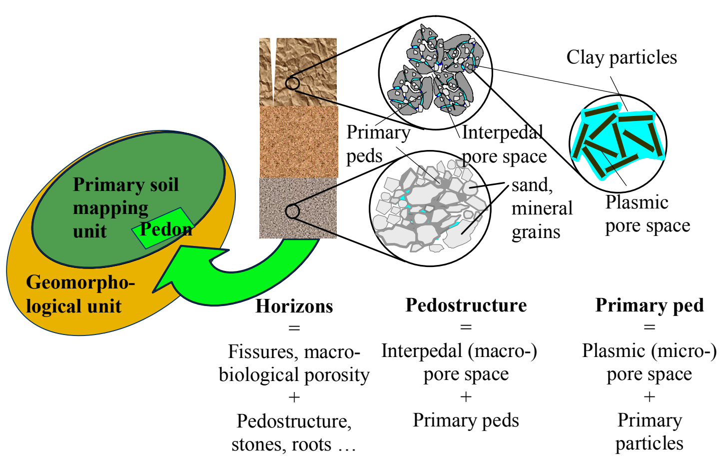

Fig. 1. External and internal hydro-functional scale levels of the soil organization

the non-rigid structure of the soil medium. The new apparatus, named TypoSoil® [12], which measures accurately and simultaneously in laboratory the two first hydrostructural characteristic curves of the pedostructure, namely, the shrinkage curve and the water retention curve, allowed us validating the theoretical equations of these curves [13,9,10]. It was recently put available on the market (2014). The corresponding pedostructural parameters, characteristics of both curves, are then accurately determined by fitting the measured curves with their physical equation [14]. Regarding the other two curves, hydric conductivity and swelling curves, the specific equipment required for their measurement exists, but the characteristic parameters of these curves cannot be determined without a preliminary determination of the hydrostructural parameters of the sample, using TypoSoil®.

These 4 hydrostructural functions of the pedostructure are taken in charge by the soil-water model Kamel® [15,11] which uses their theoretical equations for modeling the soil-water dynamics within the internal organization of a pedon (Representative Elementary Volume of a soil profile in a Soil Mapping Unit). Other information about the horizons of the pedon is of course needed, including the percentage of pedostructure in each horizon, the thickness of each horizon, the percentage of other organizational volumes such as macropores, roots, stones, and so forth [11].

2.3 A Specific Laboratory at the Hearth of the New Discipline

Hydrostructural Pedology involves the "mechanistic" articulation between three scientific fields of investigation: the field, the laboratory and the geo-referenced hydro-functional soil mapping units. The latter being the base layer of the NEO-GIS (Natural Environment Organization-GIS), a modeling platform containing all georeferenced information for interdisciplinary studies of the soil-plant-atmosphere system.

A hydrostructural pedology laboratory, with its specific equipment including TypoSoil®, is then required (Fig. 2) to determine the pedo-structural characteristics of each soil horizon, to organize the data in relation to field operations (soil sampling, mapping, experiments) and with the georeferenced hydro-functional soil mapping units [14].

A precise methodology of measurement for the four characteristic curves and the determination of their parameters are fully described. These parameters, named pedostructural parameters, are the characteristics of a soil horizon required by Kamel® to model the hydrostructural functioning of a pedon at its different scales of functioning and at every depth in the soil. They constitute the basic information about the soil identity and its behavior that must be stored in soil data bases and soil GIS according to the

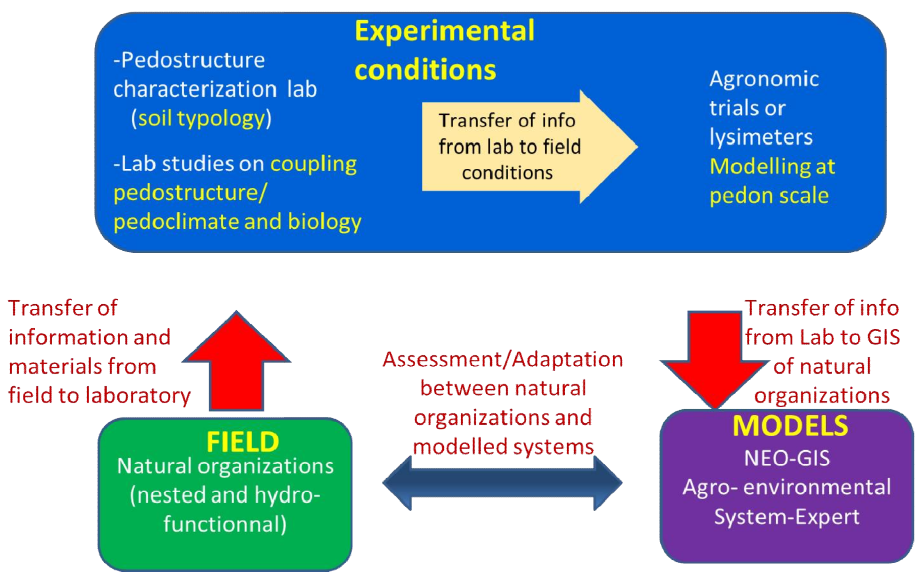

Fig. 2. The hydrostructural pedology laboratory (in blue) in relationship with the field (sampling) and the soil mapping (NEO-GIS) for the soil plant atmosphere system modelling

hydrostructural pedology paradigm. A new method for studying the water holding properties of soils using their pedostructural parameters measured by TypoSoil, was recently proposed [16].

3. IMPLICATIONS IN AGRO-ENVIRONMENTAL SCIENCES

3.1 A New Discipline Taking Place beside Hydro-pedology and Hydrology

In the new discipline, hydrostructural pedology represented in Fig. 3 [17], the soil is considered and modeled as an organized physical medium (Fig. 3a), made of solid particles, surrounded by water and surrounded by air, and always near its physical equilibrium state (thermodynamic and hydro-structural). Soil is the location of transformation of the *free water* (rainfall at soil surface, infiltrated in macropores, water table) into *green water*, which is the soil water retained by the *pedostructure*, taken up by roots (along with the *pedostructure* shrinkage), then used in photosynthesis and transpired by the crop (Fig. 3b). It is clear now that the *pedostructural water* is exactly the *green water* of agronomists. The green water content in soil is, in fact, the water content of the pedostructure, W_{ps}, at a local point in the soil. It constitutes the control variable governing the hydrostructural equilibrium state of the soil [18].

Modelling the green water is a great challenge until now for assessing the two cycles of blue (free) and green water in delimited areas in order to optimize the conversion of blue water into green water [19]. Green water is estimated according to the Soil Plant Atmosphere Continuum (SPAC) principle that identifies the green water as the evapotranspiration of plants [19] without, of course, any idea about the pedostructural water which is, as green water, a totally new concept [11]. Simulations of the water cycles in the SPAC are generally made using a soil water model like SVAT (Soil-Vegetation-Atmosphere-Transfer) that provides roughly the global soil water reserve with time. In fact, the model Kamel®, as it is based on the pedostructure and SREV concepts, is today the only soil-water model able to model distinctively the different kinds of soil water and their respective dynamics; and in particular, the pedostructural water (W_{ps}, green water) in a SREL (fine soil layer Fig. 3a) at any depth of soil [11]. Thus, pedostructure and pedostructural water (green water) become, through hydrostructural pedology, the two essential objects of study and investigation, common to agro-eco-environmental sciences. This is because, in the systemic paradigm, a primary soil mapping unit is represented by its pedon (SREV of the soil unit) and the pedon, in turn, by its horizons as characterized by their pedostructure.

In Fig. 3, we can see the place occupied by the hydrostructural pedology beside the two well-known disciplines of hydro-pedology and hydrology (Fig. 3c). The final product of these disciplines is the NEO-GIS (Natural Environmental Organization), provided they are working together according to the systemic approach and represent, locally the multi-scaled natural environment. This is a GIS of agro-environmental data (NEO-GIS), of which its first basic layer is a hydro-functional soil mapping unit: that is a systemic geo-referenced information system of a soil map built according to the hydrostructural pedology methodology. Thus, Kamel® can use the NEO-GIS information to model both cycles of water (green and blue) in each soil mapping unit and then integrate the results over the entire mapped zone.

3.2 Two Kinds of Modeling the Water-soil Couple in the Natural and in the Societal Environment

Fig. 4 presents a general and ideal picture of the activities of characterization and modeling in agro-environmental sciences for a sustainable development of a country that could exist in fact, if the new paradigm of hydrostructural pedology is accepted and put in practice [20]. It shows the two environmental modeling cycles, global and local, which are necessary for principle, to formulate all aspects of the nature-society relationships. On the right side of the figure, the cycles are illustrated: the assessment (inventory, mapping), hydro-functional characterization and hydro dynamics modeling (simulation of fluxes, processes, productions) of the soil-plant-atmosphere organization. Data obtained in these operations are necessarily at the basis of any program of installation and/or optimal and sustainable management of agro- or ecosystems which are simulated on the left side of the modeling cycles, in which all societal constraints have to be taken into account.

However, the global modeling cycle (black line) corresponds to the current modeling approach of the agro eco-environment (based on the REV concept) while the local modeling cycle (red two-way arrows) is not yet installed or put into practice. So the agro-environmental modelling today cannot be other than a global approximation of the reality at the soil surface, contrarily to the *local cycle* (red two-way arrows) which is a physical, systemic and mechanistic modelling according to hydrostructural pedology paradigm.

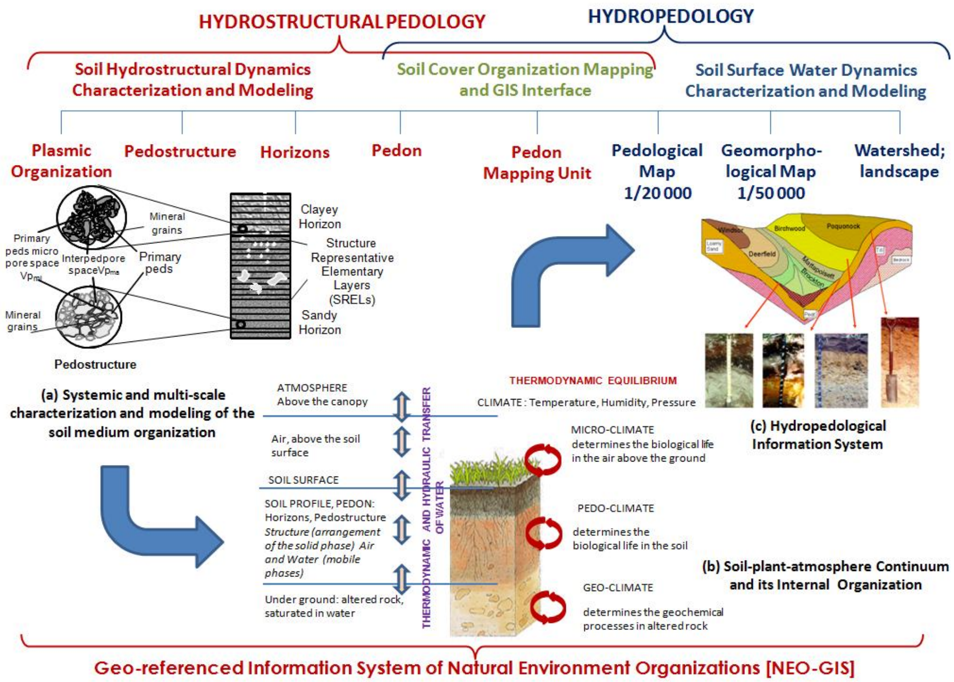

Fig. 3. Hydrostructural Pedology: A new discipline in earth sciences [17]

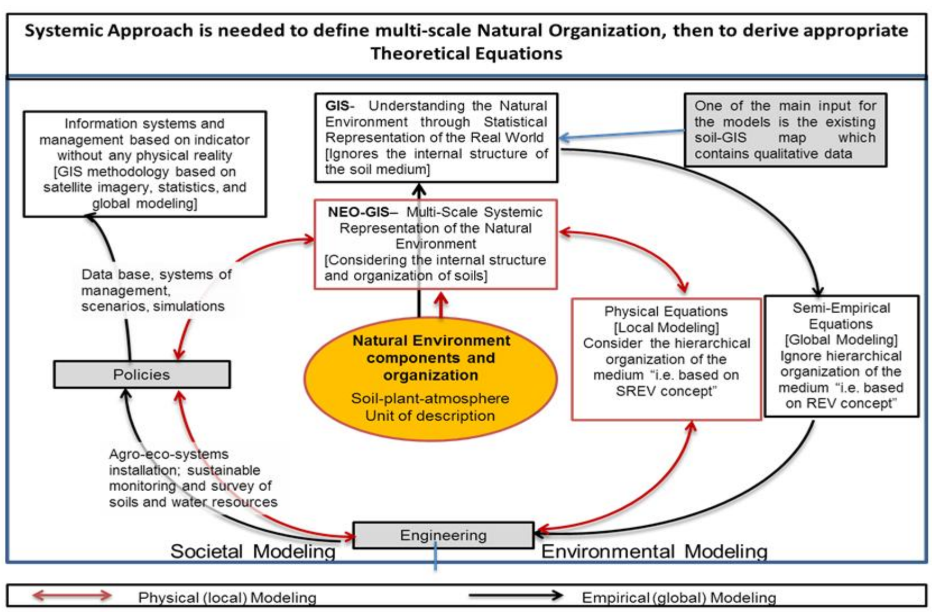

Fig. 4. The dual, local and global, cycle modeling of the water-soil couple in the natural environment (ecosystem) and in the societal environment (agro-ecosystems) [20]

4. CONCLUSION: THE NEW GLOBAL CHALLENGE OF AGRO-ENVIRONMENTAL SCIENCES

In fact, according to Fig. 4, we can see that the two modeling cycles differ already from the beginning due to the representation of the internal organization of the natural environment which is fundamentally different in the two cases:

- One, represented by the red solid line, recognizes the hierarchical organization of the medium and can be named "local-scale modeling" because it takes reference to the soil structure;
- The other, represented by the black line, conceals any internal organization by using the concept of Representative Elementary Volume, and thus cannot be other than a "global scale modeling approach" where any reference to the structure of the medium is eliminated.

Therefore, only the red cycle (red two-way arrows), where relationships and transfers of scale are based on physical and systemic approach, makes it possible a return to the reality of the natural organization, and thus for a true estimation of the real evolution or changes of this natural organization (for example, ecosystems). This modeling cycle does not exist today, which is reflected in the awareness of the central role of soil, at all scales, in agricultural and environmental management issues [21], and especially the lack of method to take this into account.

So the great challenge today should be the installation of this physical modeling cycle for linking the two approaches, local and global. The NEO-GIS, specific product of the physical and systemic (red) cycle modelling, should be the support of information on which the global (statistical) modeling has to be based for a good estimation of the reality. This implies the development of the hydrostructural pedology paradigm around the world, to allow the universal development of the NEO-GIS for the optimal and sustainable management of soils and water in any agricultural or ecological zone or region.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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