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An essay on the possible improvement of soil fertility understanding by cooperation with soil physics

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Abstract

In soil physics, states and rates are described using advanced mathematical tools and the results not always conduct to practical recommendations. Soil fertility is based mostly on empirical knowledge and the research leads to recommendations for optimized use of fertilizers and other resources to improve crop performance or reduce environmental impacts. Soil physicists can be of significant help in the challenge of making soil fertility less empirical and more independent of site specific conditions. In this paper some possible contributions of soil physics to questions of soil fertility are described, and the difficulties constraining this cooperation are discussed. Bibliographic survey results indicated that modern soil physics allows automated measurement, modeling, and prevision of important dynamic soil characteristic that are related to the chemical behavior of soils and to plant nutrition efficiency. A closer interaction could turn soil fertility studies less empirical and wider applicable and soil physics more practical for the understanding and management of agronomic processes.

Key words: soil physics, modelling, nutrient transport

Zusammenfassung

Ein Beitrag der Bodenphysik zur Interpretation von Untersuchungen der Bodenfruchtbarkeit

In der Bodenphysik werden Zustände und Zustandsänderungen mit Hilfe komplexer mathematischer Methoden beschrieben - mit dem Erfolg, dass die Ergebnisse nur geringen praktischen Wert haben. Die Erforschung der Bodenfruchtbarkeit erfolgt dagegen meist rein empirisch mit dem Ziel, das Pflanzenwachstum zu verbessern, Ressourcen zu sparen oder Umweltwirkungen zu verringern. Bodenphysikalische Methoden und Erkenntnisse können jedoch in großem Maße helfen, die Ergebnisse von Bodenfruchtbarkeitsstudien weniger empirisch darzustellen, besser zu verallgemeinern und übertragbarer zu machen. Der Beitrag gibt einen Überblick zur Entwicklung bodenphysikalischer Forschung sowie ihrer grundlegenden Modelle und Methoden. Es werden für ausgewählte Forschungsthemen zur Bodenfruchtbarkeit mögliche Beiträge der Bodenphysik diskutiert.

Schlüsselwörter: Bodenphysik, Bodenfruchtbarkeit, Modelle, Nährstofftransport

1 Introduction

In general, physics studies natural phenomena and establishes rules to explain and predict them. Considering that basically everything is nature, it might be questioned why there is a need for other sciences like chemistry, biology or medicine. Wouldn't an adequate physical description of how atoms and molecules interact make chemistry unnecessary? Wouldn't the physical description of chemistry and geography make biology redundant? If one could describe, physically, a human body and its environment, why keep on studying medicine? However, the agreement to the previous statements would bring us far from common sense. The existence of all sciences can be explained due to the fact that problems have to be solved before knowing their exact explanation.

Following this general rule, soil physics deals preferably with the understanding and description of soil transport processes, while other branches like soil conservation or soil fertility have as their main scope to solve practical problems. The 'Handbook of Soil Science' (Sumner, 2000) quotes a historical citation at the beginning of each section. For the soil physics section, it presents a quote by the Greek philosopher Plato: 'The soil was deep, it absorbed and kept the water in the loamy soil, and the water that soaked into the hills fed springs and running streams everywhere'. In the soil fertility section, the Irish author Jonathan Swift is acknowledged when writing 'And he gave it for his opinion that, whoever could make two ears of corn or two blades of grass to grow upon a spot of ground where only one grew before, would deserve better of mankind, and do more essential service to his country, than the whole race of politicians put together'. These two quotations may be useful to illustrate the difference in the philosophy of soil physics and fertility. While a soil physicist intends to describe and explain the functioning of the soil system and its interactions with the environment, those who deal with soil fertility want to solve practical problems. These two ways of thinking and prioritizing are different, as shown by Passioura (1996) in his paper on "Simulation Models". He classified as "Scientists" those who are involved with the understanding of processes, while "Engineers" solve problems. This quotation differs substantially from Louis Pasteur's (1874) statement: "No and a thousand times no, there is no single branch of science which could be entitled applied sciences. There is science and application of science which belong together like the fruit and the tree which bears it."

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Table 1
Contributions (%) in "Soil Science Society of America" journal in two historical periods by type and research method

		Year	Soil physics[1]	Soil fertility[2]
Type	Basic	1937-39	100	26
		2000	98	35
	Applied	1937-39	0	40
		2000	2	35
	Basic/Applied	1937-39	0	34
		2000	0	30
Method	Model	1937-39	0	0
		2000	20	5
	Methodology	1937-39	23	3
		2000	27	10
	Theory	1937-39	0	3
		2000	15	5
	Experiment	1937-39	77	94
		2000	38	80

[1] = Considering full papers from the soil physics section of Soil Science Society of America Proceedings years 1937, 38, and 39 (n = 35) and Soil Science Society of America Journal year 2000 (n = 56).

[2] = Considering full papers from the soil fertility section of Soil Science Society of America Proceedings years 1937, 38, and 39 (n = 35) and Soil Science Society of America Journal year 2000 (n = 20).

Essentially, soil physics deals with the description of the physical aspects of the soil system and transport processes. Rules and laws are generally valid for all depths and for all types of soil. States and rates are often described using advanced mathematical tools and the results are not expected to result in practical recommendations. In soil fertility the main scope is the examination of the factors that control the availability of plant nutrients, soil tests for assessing nutrient sufficiency, soil management practices for the efficient use and environmental safety of fertilizers. Results are based on empirical equations with strong support of statistical tools. The results are restricted to certain circumstances (soils, crops, climate) leading to practical recommendations. As an indicator for the actuality of this statement, the papers published in the Soil Physics and Soil Fertility section of the Soil Science Society of America Proceedings/Journal from 1937-1939 and 2000 were classified in basic, applied or basic/applied and in methodology type (model development, methodology, theory or experimentation) and shown in table 1. In both periods soil physics was almost only dealing with basic questions, whereas soil fertility studies involved a major part of applied research. Also in both areas, especially in soil physics, there was an increase in the development of theoretical research and modeling, while in soil fertility methodological studies increased.

Any approach between research in soil physics and soil fertility will benefit both areas. Soil fertility can be assisted by soil physics because the processes that determine soil fertility are also influenced by physical processes. Soil fertility studies still rely preferably on stationary data, which is not in line with natural systems where stationarity merely exists. Modern soil physics allows automated measurement of dynamic soil characteristic, their modeling and prevision. A closer interaction between soil fertility and soil physics studies could turn soil fertility studies less empirical and even wider applicable.

2 Interfaces between soil physics and soil fertility

Nutrient dynamics are affected by abiotic factors e.g. soil solution pH, soil mineralogy, quantity and types of organic matter and biological factors. Soil physical factors, mainly water content, temperature and oxygen supply influence both, abiotic and biotic processes. This explains why physical factors affect to a great extent soil fertility. Interrelations between physical, chemical and biological factors involved in soil chemical fertility are sketched in fig. 1.

3 Describing transport processes in soils

Any change in the soil system involves transport of matter or energy and soil physics' principal area is the study of transport processes. These include the transport of water, ions, gases and heat in the soil. A central objective of research in soil physics is to describe related transport processes (3.1) and to measure the involved parameters (3.2). The quantification of fluxes allows calculating how concentrations change along time. With adequate parame-

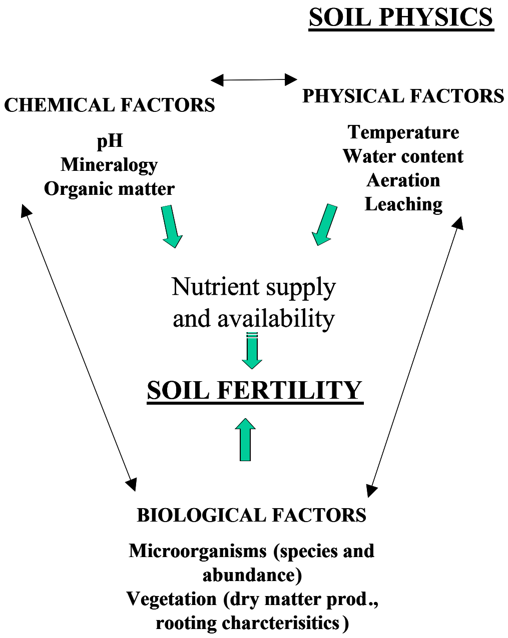

Fig. 1
Interrelations between physical, chemical and biological factors involved in soil fertility

Table 2
General flow equations applicable to soil physics

Flow	Equation	State variable	Rate variable
Water "Darcy"	$q_{water} = -K \frac{d\psi_t}{dz}$	hydraulic conductivity (K)	potential energy gradient ($d\psi_t/dz$)
Gas "Fick"	$q_{gas} = -D_g \frac{d[gas]}{dz}$	gas diffusivity (D_g)	gas concentration gradient ($d[gas]/dz$)
Ions	$q_{ion} = -D_i \frac{d[I]}{dz} + q_{water}[I]$	ion diffusivity (D_i)	ion concentration gradient ($d[I]/dz$)
Heat "Fourier"	$q_{heat} = -\lambda \frac{dT_t}{dz} = -\frac{\lambda}{c}\frac{dH}{dz}$	thermal conductivity (λ)	temperature gradient (dT/dz)

ters and validated models, soil moisture, temperature and aeration regimes can be used to predict other soil processes.

3.1 Modeling flow processes

The main tool in describing transport processes is the general flow equation. In 1856, the French engineer Henry P.G. Darcy (1803-1858) suggested a general equation that describes fluid flow through porous media. Darcy's law relates water flow to potential energy gradients. Gas flow is related to gas concentration gradient by Fick's law of gaseous diffusion. Heat flow relates to the temperature gradient in Fourier's law of heat diffusion and ion movement in the soil is described by the ion concentrations and the water flow (table 2).

These equations include a driving (or rate) variable and a resistance (or state) variable. State variables are known as hydraulic conductivity, gas diffusivity, ion diffusivity and thermal conductivity, and they are highly dependent on soil water content.

Flow equations allow the calculation of concentration changes, combining them to the mass conservation equation or, in the case of heat flow, to the heat conservation equation, resulting in differential equations. These can be solved analytically imposing boundary conditions that are specific conditions under which the dependency of variables is described. The resulting solutions will be valid only under those boundary conditions. It follows an example for oxygen in soils: assuming the boundary conditions (1) that the oxygen consumption rate is constant along depth; (2) that soil porosity and air-filled porosity do not vary with depth and (3) that gas flux tortuosity is described by the Millington & Quirk (1961) equation. Considering this conditions the following equation for the steady state oxygen concentration as a function of depth in a soil profile can be deduced:

$$[O_2]_z = [O_2]_{atm} - \frac{C_{O_2}}{\frac{\beta^{10/3}}{\alpha^2} D^a_{O_2}} \left(\frac{z^2}{2} + z.z^e \right)$$

where $D^a_{O_2}$ (m^2 s^{-1}) is the diffusivity of oxygen in air; $[O_2]_{atm}$ (kg m^{-3}) is the atmospheric oxygen content; C_{O_2} (kg m^{-3} s^{-1}) is the oxygen consumption rate in the soil; z_e (m) is the depth until which oxygen consumption occurs, roughly equal to the maximum rooting depth; α (m^3 m^{-3}) is the total soil porosity and β (m^3 m^{-3}) is the air-filled porosity.

As an example, fig. 2 shows oxygen concentrations related to soil depths comparing a high and a low level of air-filled porosity. The results in fig. 2 show that the lower β leads to oxygen depletion in the rooting area below about 0.38 m, while at the higher β no depletion occurs. Generalized, this equation can be used to predict at what depth oxygen supply will be insufficient for root growth or what is the minimum required value of air-filled porosity under certain circumstances to guarantee sufficient oxygen supply for plant roots. This equation will be valid under the presumed boundary conditions.

If time and space steps are chosen sufficiently small, state variables can be considered constant within one step, allowing flow computations. This procedure described for instance by Matthias & Hernández (1998) for heat flow, by Harter & Yeh (1998) for water flow and by Fang & Moncrieff (1999) for gas flow, has only recently gained importance due to the availability of increasing data processing facilities. Its main advantage is the absence of restricting boundary conditions, increasing the possibility of application.

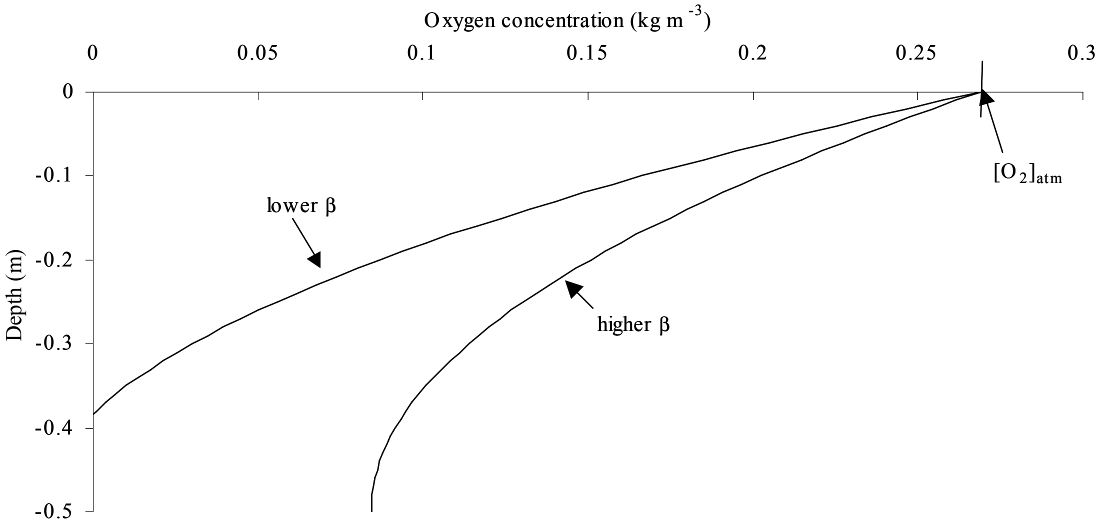

Fig. 2
Steady state oxygen concentration along depth for a high ($\beta = 0.140$ m^3 m^{-3}) and low ($\beta = 0.123$ m^3 m^{-3}) air-filled porosity in a soil with $D^a_{O_2} = 1.78 \,.\, 10^{-5}$ m^2 s^{-1}; $[O_2]_{atm} = 0.269$ kg m^{-3}; $C_{O_2} = 1.5 \,.\, 10^{-7}$ kg m^{-3} s^{-1}, $z_e = 0.5$ m and $\alpha = 0.5$ m^3 m^{-3}

3.2 Measuring water and ion concentrations in soil solutions

Water content

The main soil characteristic to be determined in almost all transport studies is the soil water content. It influences all state variables and some of the rate variables. Soil water content can be indirectly measured using tensiometer - matric potential, gamma counter - attenuation (Reginato & Van Bavel, 1964), neutron probe - neutron thermalization (Gardner & Kirkham, 1951), thermometers - thermal conductivity, ohm-meters - electrical resistance or TDR (Time Domain Reflectometry) - dielectric constant (Topp & Reynolds, 1998). All of these methods have advantages and disadvantages. Thermometers or ohm-meters, may sometimes show weak correlations to water content. Others, like gamma- or neutron probes, involve radioactive material that is not allowed in most field situations. Recently, TDR is becoming more popular, mainly because it can be easily automated. The main problem with using TDR is its calibration, which has not proven satisfactory in some situations (Noborio, 2001).

Ion concentrations in soil solution

Soil solution concentrations are commonly analyzed in laboratories in liquid samples gained through vacuum extraction employing ceramic cups. This procedure is laborious and time consuming. Alternatively, estimates of total solute concentration can be obtained using ohm-meters or TDR equipment. Especially the TDR technique is promising, allowing simultaneous and automated measurement of water content and ion concentration (Noborio, 2001).

4 Application of soil physics to soil fertility studies

The proper understanding of soil management impacts changing temperature, water content, oxygen and other soil physical factors on nutrient release would yield synergisms for all branches of soil science.

Soil physicists apply their knowledge to irrigation and drainage, soil conservation, or rural mechanization, but usually little interest in chemical soil fertility questions can be observed. In part, this is due to a lack of tradition and, consequently, education. Soil physics is taught in theories, and little is done to transform these theories in applications. Even if this is done, it is easier to extend these theories to the more "physical" applications mentioned above, than to link them, through chemistry and biology, to soil fertility, which emphasizes empirics over physics. Due to the gap that has to be overcome to describe biological systems on a more physical basis, soil physics and fertility are so far apart.

Recent research needs in soil fertility studies demanding assistance of soil physics are located in the description of soil water content and availability for fertilizer efficiency. A challenging field of research is the hydraulic storage of nutrients. This is of particular interest for understanding the sulfur supply of crops (Bloem et al., 1998). Investigating the S balance of crops reveals a great gap between inputs and outputs in agro-ecosystems. A healthy oilseed rape crop in Northern Germany removes up to 100 kg ha^{-1} S, whereas the annual atmospheric S input in that region is below 10 kg ha^{-1} S (Eriksen et al., 1998). The traditional explanations for this gap are assimilation of gaseous S compounds or release of sulfur from organic matter turned out insignificant. More likely is that additional sulfate is delivered in significant amounts by ground- and soil water sources and because of the minor interaction of sulfate with soil adsorbers and its high solubility it is stored and transported to a great extend in or through soil micro-pores. Without taking into account this physical aspects of nutrient storage recent teaching books still unjustified consider direct assimilation sulfurdioxide and mineralization as significant sources of the S supply. Another aspect of transport which can not be fully understood by soil chemistry and soil biology alone is the physical protection of nutrient resources from microbial attacks as described by Eriksen et al. (1995) for S in organic matter.

Precision agriculture (Haneklaus & Schnug, 2002) aims for a better efficiency of fertilizers by considering soil fertility parameters. For this it is not sufficient just to patch raster data together, but to understand the interaction between the pixels and the transport of matter and nutrients through landscapes which indispensable requires the three dimensional modeling of water fluxes.

This simple list of examples where soil physics supports fertility studies can be largely extended when beside water fluxes solid transports through landscapes by erosion processes are included.

5 Conclusions

While soil physics is advancing in developing models and measuring techniques to describe and understand transport processes in the soil, soil fertility advances more empirically in solving problems related to plant nutrition. A logical assumption would be that soil physicists could be of great help when trying to make soil fertility studies less empirical and less dependent on specific conditions.

The different working philosophy of soil fertility researchers (problem solvers) and soil physicists (describers) and the fact that (micro)biology is essential to soil fertility and is difficult to be dealt with by soil physicists, makes that little cooperation exists between the two areas.

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