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Review Article

Advancements in Soil Physics and its Impact on Sustainable Agriculture

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ABSTRACT

Enhancing crop productivity with higher input use efficiency without any damage to the soil and water resources is a big challenge to Indian agriculture. Soil is a complex system having physical, chemical and biological properties which differ from soil type to soil type. These properties/characteristics play an important role in deciding the response of any management imposed and thus ultimately govern the soil productivity and inputs use efficiency. It is, therefore, important that before developing any technology for the judicious use of inputs, these characteristics including soil-water-plant relations are well understood. In the recent past various advancements have been made to understand the various soil physical processes and the flow mechanism of water, gases and heat into and from the soil profile which affects the soil environment and the atmosphere above it. Different models have been developed with an attempt to solve many problems related to complex and dynamic soil-water-tillage-nutrient-plant system. Also, techniques have been developed for rapid and precise estimation of various kinds of abiotic stresses which have a bearing on plant growth, grain yield and judicious use of various inputs in agriculture in order to arrive at sustainable and conservation agriculture. Our knowledge on the subject, however, is still limited owing to the complex nature of the soil system. There is need to study this dynamic system in-depth in multidisciplinary mode, including the root system architecture with respect to water and nutrient uptake and mitigation of various kinds of plant abiotic and biotic stresses. This paper discusses, in brief, the various advancements made in the area of soil physics and their impact on sustainable agriculture.

Key words: Soil Physical Process, Soil Water, Soil Air, Soil Heat, Soil Physical Environment

Introduction

Although, soil physics is the youngest branch of soil science, yet it is a very important component of soil science and soil health for sustainable production and resilience of soil resources. Among different disciplines of soil science, soil physics has prime responsibility of soil physical health protection, maintaining its physical health and structure so that it may efficiently perform the functions of water, nutrient, air and heat transmission, filter the toxic elements and act as a healthy habitat for soil life. The history of soil physics is believed to have started with the 1919 Soil Science article by Willard Gardner (father of modern soil physics). The article was an important step forward in the studies of water flow in unsaturated soils, leading to the discovery of the Richards equation. He was the first to actually write the one-dimensional form of the macroscopic mass balance equation. For horizontal flow, he formulated, by analogy

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with Stokes law for the motion of a particle falling through a viscous liquid, a linear relationship between the macroscopic velocity and the gradient of the curvature pressure (i.e., he postulated Darcy's law).

In fact, physical properties of soil have been noted in numerous cultural contexts, and it would be difficult to identify at just what point in historical time, observations of such properties were sufficiently analytical, or measured with sufficient care, to be referred to as scientific (Gardner, 1986).

With the advancement in science and technology in other sectors over a period of time the subject of soil physics has undergone many developments simultaneously. The developments have taken place in basic understanding of physical, mechanical and hydrological properties and processes of soil, its impact on environment, agricultural production and sustainable use of natural resources especially through the use of innovative sensors, soil databases and modeling techniques employed into soil water relationship and environmental monitoring. With the advancement in technology and instrumentation even the determination of soil parameters have become relatively easier, more accurate and bit faster.

Understanding Soil Physical Processes

The dynamics of matter and energy (water, gases and heat) within the soil system are the important processes that rely upon the soil physical environment. To begin with water, it is established that after rainfall or irrigation event, various water flow processes in the soil, both in saturated and unsaturated phase, govern the entry of water into the soil profile and its loss as runoff and evaporation. The soil surface conditions like looseness, compactness or presence of crop residues on the soil surface play a significant role in determining the magnitude of these flows. The sustainable and conservation agriculture aims at more entry and less runoff of water to augment the underground water reserves and recharge the soil profile to support vegetation. Soil surface manipulations, land configurations and retaining crop residues at the soil surface in conservation tillage mode conserves moisture, prevents soil splash through rainfall drop impact and thereby minimizes loss of fine soil particles, nutrients and precious soil biota in runoff water. Similarly, the movement of gases in soil may be independent or coupled with vapour phase and heat. In soils, many physico chemical and biological processes take place which depend on soil air and temperature. The soil organisms and plant roots need supply of oxygen into the soil for respiration and emit CO_2 and the soil does an exchange process for these gases. Before any management practice is devised which can favorably regulate these processes and maintain or enhance soil health, conserves soil and water with higher crop productivity and input use efficiency it is important to understand various soil physical processes which govern the flow of water, gases and heat within and from the soil system and their impact on root and plant growth.

Various advancements in the recent past have taken place in understanding the flow mechanism of water, gases and heat into and from the soil profile which affects the soil environment and the atmosphere above it. These processes have a direct bearing on conservation of soil and water, the two most important natural resources and also on market purchased costly inputs like seed and fertilizer. These processes are briefly discussed below.

Water flow mechanism through soils: When water is delivered at soil surface by irrigation or precipitation, its movement in soil is of three types viz. saturated flow, unsaturated flow and vapour flux. *Saturated flow* takes place, when soil pores are completely filled with water (when water potential is >-1/3 bar) and water moves mainly due to gravity. Originally the flow process was explained by famous Darcy's Law which states that water flux is directly proportional to the hydraulic gradient:

$$q \propto \Delta H/L \text{ or } q = -\mathbf{K_s}^* \, \mathbf{\Delta H/L},$$

where, q = flow rate /unit cross sectional area; ΔH =water head; L = length of soil column; and Ks =saturated hydraulic conductivity.

But classical forms of Darcy's equation apply to fluids flowing at low velocity through a non-swelling granular medium. They do not take into account the physico-chemical forces (Vander Waal's attractions, electrostatic repulsions and surface hydration), present in swelling colloids (clay particles/ platelets). Swelling clay particles consist of clusters of platelets and adsorbed water which swells under imbibitions and shrink under desiccation causing the macroscopic behaviour of clays to differ significantly from granular media.

If there are strong interactions between fluid phase and solid, such as occurs in montmorillonite clays, the above form of Darcy's law no longer applies (Karalis, 1993; Kim *et al*., 1992; Eringen, 1994). For systems, that are more complicated (swelling media and multi phase flow), Darcy's law has been heuristically extended by postulating the dependence of K on additional variables such as porosity and saturation. Therefore, in the current formulation the Darcy's law is derived (Achanta *et al*., 1994; Cushman, 1990) by linearizing about average velocity of miscible liquids through solids for a single constitutive fluid flowing through a swelling colloid and counting for volume fraction of fluids and pressure in the fluid.

Further, at the areal scale of water flow (flow through surface depressions and discontinuous layers with lower or higher permeabilities causing preferential flow), applications of Darcy equation is no longer practical. One approach for evaluation of water movement at such a high scale is to employ aerial mass balance equation (Hendrick and Walker, 1997).

In swell shrink clayey soils, the cracks, macro pores/ bio pores and inter-pedal pores conduct the water very rapidly, which is called as preferential/ bye-pass flow, which do not represent actual soil property, but may lead to rapid transport of contamination to ground water. That is why in such cases infiltration is studied at low-tensions using tension-infiltrometers which excludes the pores that are larger than corresponding size, from actively conducting the water. Therefore, the problem about which Daniel Hillel showed a concern in 1980, in his book '*Applications of Soil Physics'*, is solved with the advent of low tension infiltrometry. In structured clay soils such as vertisols, the practice of no tillage/ reduced tillage leaves surface residues that protect the soil from quick desiccation and reduce the volume of cracks. Still the remaining cracks may result into preferential flow of water and hence the low tension infiltrometers may come handy in alleviating the bypass flow in determination of infiltration rate.

The infiltration mechanisms are explained by various other equations such as Green- Ampt equation, Philip's Equation, Horton's equation, Kostiakov's equation etc. Green and Ampt equation takes into account many variables such as suction head, porosity, hydraulic conductivity and time that other methods such as Darcy's law do not. Horton's equation also provide for varying total volume infiltered at any point of time and the equilibrium infiltration rate as is done by Green and Ampt method. Rawls *et al*. (1982) modified this equation for soils with a crust by multiplying hydraulic conductivity with a crust factor (CF).

After infiltration the water percolates through substrata carrying the nutrients and other dissolved salts as saturated flow. As the gravitational water partly drains from the large water filled pores and air enters the drained spaces, the water flow rate is generally reduced and is called *unsaturated flow*, where smaller pores hold and transmit the water. The driving force here is the matric potential gradient derived from surface tension inside the pores (capillarity) and adhesion to soil particles. The water moves from moist soil to dry soil and from thick moisture films to thinner ones.

Moisture Retention and Release: The unsaturated flow is of great importance as after rain/irrigation, water movement is slower, water is retained against gravitational force and hence it makes water available to plants for a longer period even after recession of the rain. This happens due to moisture retention and release characteristics of soil, which again depends upon soil porosity, pore size distribution, texture, and also affected by external factors like temperature, atmospheric demand and land management. There is a strong relationship between matric potentials and moisture retentions by soil which we call soil moisture characteristic/retention curve (SMCC/ SMRC). Moisture is held by soil in various quantities under various matric tensions and plants have to exert pressure higher than that matric tension to extract the water. This information of SMRC of soil is necessary to assess water availability to crop. It is not that all the soil water at all the matric tensions is available to crop. It is available only between matric potentials of -1/3 bar (field capacity) and 15 bars (permanent willing point) and hence is called plant available water capacity (PAWC) of a soil. So, water is released by the soils within this range upon the gradual increase of negative pressure exerted by roots to overcome the tension with which water is held within soil.

In order to explain soil-water plant relations in a reliable way, matric potential values are required to calculate the flux between layers or towards plant roots. As the laboratory determination of SMCC is time consuming and expensive, several empirical equations based on texture were developed for predicting SMCC (Botha and Eisenburg, 1993; Teshai, 2002). Procedure for correcting retentive values for the presence of stones in soils was developed by Knight and Moolman (1992) and Van Deventer *et al.* (2002). Smith *et al.* (2001) related the water relation characteristics of forest soils to soil compaction. Rawls *et al.* (1982, 1983) were leaders in developing regression equation to estimate θ(h) from soil texture, bulk density and O.M content. Can these equations be used to estimate θ(h) curves due to change in bulk density with tillage and reconsolidation? Ahuja et al (1998) reviewed that changes occur only in large pores at the wet end of the SMCC and they proposed semi empirical methods for determining changes caused by tillage.

Evaporation: The upward movement of water from soil to the atmosphere in the vapour phase is another important mechanism of water movement in and from the soils. The rate of diffusion of water vapours through the soil is proportional to the square of the effective porosity, regardless of pore sizes. The finer the soil pores, the higher is the moisture tension under which maximum water vapour movement occurs within soil, which helps in survival of plants. In rain fed, semi arid areas or dry climates, evaporations from soil is a major wastage factor which can amount to 60-70% of the annual rainfall. Van Zyl and De Jager (1997) attempted to develop a procedure for estimating evaporation from cropland using data from weather stations. Calculation from relatively simpler measurement of total ET has been described by Hatting *et al.* (1992) and found to be satisfactory in field conditions with objective of seeking ways of reducing ET. Botha *et al*. (2001) studied the influence of different mulches on ET and obtained useful results. Many workers used micro lysimeters to measure ET from soils differing the texture and under range of soil covers and found that surface covers larger than 70-80% are required to reduce the ET rates. The evaporative losses from a soil can be reduced by various management practices like conservation tillage (Acharya *et al.,* 1998) organic/ plastic mulching, spreading manure or compost, green manuring and other surface manipulations in order to prolong the water availability to crop plants.

Flow of gases and heat through soils: The movement of gases in soil may be independent or coupled with vapour phase and heat. In soils, many physico chemical and biological processes takes place which depends on soil air and temperature. The soil organisms and plant roots need supply of oxygen into the soil for respiration and emits CO_2 and the soil does an exchange process for these gases. If the supply of O_2 and exchange of CO_2 is not adequate, the plant growth is retarded and crop yields may be hampered.

The exchange of air takes place through soil pores and is governed by Fick's law of diffusion which states that, flux of gas across a plane is proportional to the concentration gradient:

$$q_g = - D * dc/dx$$

where q_g = flux of the gas per unit cross sectional area per unit time in the x direction, D = diffusion coefficient, and dc/dx = concentration gradient.

However, application of Fick's law to porous media has been questioned by a number of investigators including Thorstenson and Pollock

(1989), Abirola *et al*. (1992), and Webb (1998). Stephan-Maxwell method too was an extension of Fick's law (Bird *et al*., 1960) for a multi-component mixture. Both these equations apply to gas diffusion in open space, not in porous media. More recently the dusty gas model (DGM) takes the gas transport equation a step further by including the effect of porous media as a dusty gas component of the gas mixture. The kinetic theory of gases is applied to this dusty gas mixture. Knudsen diffusion (molecule-wall interaction) is inherently included in the model and a porous media factor similar to that described for advective diffusion model (ADM) is used. Also, Fick's law is valid strictly for isothermal, isobaric and equimolar counter current diffusion of a binary gas mixture. So in binary gas mixture if flux of each gas component depends on the flux of other gas component, then Fick's law no longer applies. Because Fick's law predicts the diffusion of only one component, variations in concentrations of other components are attributed to other processes. Unlike Fick's law which can consider only binary gas mixture, the Stefan-Maxwell equations or DGM can evaluate multicomponent gas transport. Also in order to estimate diffusion co-efficients from soil properties, such as porosity, tortuousity, and water content, several empirical equations have been published (Troeh *et al*., 1982, Jin and Jury, 1996; Moldrup *et al*., 2000). For instance Pumpanen *et al*. (2008) used the equation of Troch et al to estimate diffusion co-efficients for the calculations of CO_2 fluxes in soils and from the soil to the atmosphere. Pinginatha (2010) assessed several empirical equations for the same purpose.

The gas exchange rate across soil and atmosphere decides the soil air composition and to some extent the concentration of various gasses in atmosphere. Soil air composition is regulated by respiration (by roots and microbes), soil organic matter content, soil moisture, porosity, tillage and biological activity. Soil management practices that encourage good aggregation, porosity and drainage may ensure better rates of gaseous exchanges and good crop growth. Under inundated soil conditions, the emission of methane is elevated. Also the application of N-fertilizers may enhance N_2O emission to the atmosphere. The CO_2, CH_4 and N_2O gases (GHGs) emitted by agricultural practices in higher concentrations are contributing to global warming, on account of their radiative capacity or global warming potential. Therefore, the agricultural practices which do not burn the crop residues, retain residues on soil surface without incorporating into the soil (e.g. No tillage) as is defined in conservation agriculture, may lock the carbon on the earth, reduce the emission rates and assist in curbing the global warming. Further, the environmental consciousness of general public is challenging producers to modify farm management practices to protect water, air and soil quality.

Heat flow in soil takes place by conduction (faster movement of molecules from hot to cool end) and to some extent by convection (difference in density of conducting medium due to the temperature gradients). The flow of heat in soils is explained by Fourier's law, that heat fluxes are directly proportional to the temperature gradient across a soil system:

$$q_h = -\lambda * dT/dx$$

where q_h = heat flux per unit cross sectional area per unit time, dT/dx = temperature gradient, and λ = thermal conductivity.

However, in situations dealing with heat flow in extremely short periods of time (high frequency heat source such as laser or microwave), very high temperature gradient, very low temperature near zero or for micro scale conditions such as heat transport via biofilm, the Fourier's law breaks down and the wave nature of heat propagation becomes dominant (Hader *et al*., 2002; Tzou, 1997). Therefore this theory should be modified. In other words Fourier's law has the unphysical property that it lacks inertial effects; if a sudden temperature perturbation is applied at one point in heat conduction medium, it will be felt instantaneously and everywhere at distant points. Heat flow in a soil system depends mainly upon water content of soil. Similarly, the decomposition of organic matter mineralization of soil nutrients and movement of water and nutrients is affected by soil temperature. Low soil temperature may reduce these soil processes. Several studies (Prihar, 2000; Acharya, *et al.*, 2004) have shown that keeping soil surface covered with organic or plastic mulches moderates not only the hydro but also the thermal regime for favorable crop growth.

Modeling Soil Physical Processes

Due to complex nature of the soil system very little is known about how structure changes with time which affects the soil hydrological properties. In the last 25 years soil physicists have taken on the challenge of addressing real problems and moved from laboratory scale stands to field and landscape scales by modeling various physical properties and processes. Simpler equations have been modified and integrated to complex integrated models using fast computing by modern computers. Scope of soil physics has gradually expended towards interdisciplinary boundaries because of central role of water in agriculture systems. Soil physics research in interfacial areas include modeling the linkage of transpiration with photosynthesis, energy balance of crop canopies (Van Bavel and Lascano, 1987) crop water uptake (Campbell, 1991), root growth modeling (Benjamin *et al.*, 1996) and nutrient uptake by roots. Simulation models are used to further understand flow and transport behaviour and to perform scenario analyses in soils. Crop growth and yield as determined by weather and soil type can be understood better by soil water and nutrient dynamics along with the development of the crop. So, soil physical processes along with temporal and spatial estimation through modeling have become helpful in extrapolating the limited information from one location to other. All the soil physical processes such as evaporation, infiltration, and runoff etc which are part of the water balance can be simulated using suitable modeling techniques. Most of the crop simulation models have sub modules for water balance and solute flow which are governed by the demand and supply of water by the crops according to the environmental condition.

Some of the examples are EPIC (*Erosion/ Productivity Impact Calculator)* model (Williams *et al.*, 1984) to estimate bulk density after tillage, RZWQ (Root Zone Water Quality) model (Ahuja *et al.*, 2000) to predict soil reconsolidation after tillage, estimation of $\theta(h)$ from soil texture (Rawls *et al.*, 1982), estimates of pore size distribution as affected by tillage (Ahuja *et al.*, 1998; Or *et al.*, 2000), a model linking soil hydraulic properties to soil morphology structure and aggregation (Lilly and Lin, 2004) and simple model of soil shrinkage curve by Peng and Horn (2005). Few other important models developed are, SALUS (System Approach to Land Use Sustainability) designed to model continuous crop, soil, water and nutrient conditions under different management strategies (Basso *et al.*, 2006), HYDRUS, which models environment for the analysis of water flow and solute transport in variably saturated porous media, simulating the two- and three-dimensional movement of water, heat, and multiple solutes and numerically solves the Richards equation for saturated-unsaturated water flow and convection-dispersion type equations for heat and solute transport (www.pc-progress.com/), SoWaM (Soil Water Management) model for simulating 1-Dimensional flow in porous media (Wesseling *et al*., 2009) and Soil Plant Air Water (SPAW) model (Saxton and Willey, 2006) relating field hydrology and soil water to rainfall, temperature, evaporation and crop growth.

Water and Nutrient Uptake by Crop Roots and Input Use Efficiency

Although, for our convenience the topic is discussed separately, the soil-plant-atmosphere is one continuum and should be understood and discussed as one stream. Uptake of water and nutrient is mainly driven by soil water potential, root architecture, soil hydraulic properties, soil management practices such as tillage and climatic conditions. The role of root in water and nutrient transport is now becoming increasingly important owing to water limited situations arising due to future climate change. However, much attention has not given to water and nutrient uptake processes below ground and thus, has created a knowledge gap concerning the plant responses of nutrient and water for crop production. A better understanding of the mechanisms of water and nutrient uptake by plant roots would be vital for improving water and nutrient use efficiency in agriculture.

Root system architecture (RSA): The spatial configuration of a root system in the soil, is used to describe the shape and structure of root systems. A large number of studies confirm that deeper root systems enable plants to access water not available to shallow rooted plants, and to balance high rates of transpiration during water deficit. A range of root traits are linked to plant performance in specific environments (Lynch and Brown, 2012). The main strategies of rhizosphere management are: (1) manipulating root growth in terms of both morphological and physiological traits; (2) intensifying rhizosphere processes in terms of acidification and carboxylate exudation; and (3) synchronizing root-zone nutrient supply with crop demand by integrated soil–crop system management. Root/rhizosphere management, therefore, is an effective approach to enhance water-nutrient use efficiency and crop yields for sustainable crop production.

Root water uptake: Direct, real time, observation of water uptake by plant roots, and water fluxes through root and stem vessels is technically challenging. With the advancement in analytical techniques, instrumentation and software development it is possible to estimate plant water potential, hydraulic conductance; root water uptake and, soil water balance. The computer programs/models are used to, analyze several 3-D root architectural models viz ROOTMAP, SIMROOT and SPACSYS with ability to accurately model the root system that provides a realistic representation of root architecture in the soil and open a new vista in understanding of root water uptake. New technique based on neutron radiography (Zarebanadkouki *et al*., 2012), and magnetic resonance imaging (Stingaciu *et al*., 2013) have been introduced and tested to quantify water uptake along the roots of a living plant. This technique will help in a better understanding of root functioning and provide a database to evaluate and improve existing models.

Nutrient uptake: In addition to soil transport, nutrient uptake is controlled by the spatial distribution of roots, as influenced by its architecture, morphology and presence of active sites of nutrient uptake, including root hairs. For nutrients that are immobile (e.g. P) or slowly mobile (ammonium), a root system must develop so that it has access to the nutrients, by increasing their exploration volume. Alternatively, the roots may increase its exploitation power for the specific nutrient by local adaptation of the rooting system, and increase the uptake efficiency of the nutrient.

Different modern techniques have been used to screen plant genotypes to absorb more nutrients from soil and fractal geometry approach is one of them. Dynamic models of RSA are also often used to simulate growing root systems and integrate, from the root segment to the root system levels, interactions between root systems and their environment. The imaging technique *viz*. fluorescent imaging technique (Kanno *et al*., 2012), nuclear magnetic resonance (Ishida *et al*., 2000) and positron emission tomography (Yoneyama *et al*., 2011) are indispensable tools in understanding the nutrient uptake in root systems. Recently, an optical imaging method using Cerenkov radiation from radioisotopes has been reported to study nutrient uptake in plants. Kanno *et al*. (2012) developed radioisotope imaging techniques for real-time imaging of ionic movement. The first system, called macro-imaging, was developed to visualize and measure ion uptake and translocation between organs at a whole-plant scale. These radioisotope based imaging systems will facilitate the systematic analysis of real-time uptake of various macro- and micronutrients and open a new opportunity.

Soil environment, water-nutrient uptake and their efficiencies: A change in soil environment reflects different management practices imposed in the field. Among different tillage systems, no-tillage (NT) may have potential advantages over other tillage systems in terms of nutrient and water uptake by plants. The other advantages include increased carbon sequestration and climate mitigation potential over conventional tillage systems. Other soil physical properties benefited by NT systems are increased soil water availability and increased number of biopores that may facilitate root growth. Tillage also affects root density as well as distribution. Compared to continuous conventional tillage, rotational tillage (No-tillage/Sub-soiling) may also increase wheat crop yield and WUE by 9-11% and 7-8%, respectively. This increase in crop yield and WUE is attributed to better soil environment under rotational tillage, which provide conducive soil environment for better root growth. In general, conservation tillage results in the stratification of soil nutrients, especially of immobile nutrients like P and produces greater soil fertility near the soil surface, causing an increase in root length density near the soil surface. An interactive study of tillage and nutrients on root growth, water use, dry matter and grain yield of wheat (Gajri *et al*., 1992) showed that both deep tillage and early irrigation shortened the time needed for the root system to reach a specified depth. Subsequent wetting through rain/irrigation reduced the rate of root penetration down the profile and also negated deep tillage effects on rooting depth. However, tillage/irrigation increased root length density in the rooted profile even in a wet year. Better rooting resulted in greater profile water depletion, more favorable plant water status and higher dry matter and grain yields.

Method of water application also affects the dynamic nature of soil-water system and water use efficiency. Water use efficiency (WUE) under micro-irrigation (sprinkler and drip) systems is known to be higher than conventional flooding method. Efficiency of flood, sprinkler and drip irrigation system varies between 40-60%, 70-85% and >85%, respectively. But, the interplay between water and nutrient management plays a complex role in crop production. Because of its highly localized application and the flexibility in scheduling water and chemical applications, drip fertigation has gained widespread popularity as an efficient and economically viable method of fertigation. Precision land leveling using laser assisted land leveler equipped with drag scrapper in conservation agriculture has been successful in saving 31% water, increasing water productivity of rice by 0.36 kg grain m^{-3} water and 5.5% increase in the rice yield over traditional practice of land leveling.

Soil Health/Quality

Due to agricultural intensification with persistent use of conventional extensive tillage with removal or burning of crop residues, soil health (in terms of physical, chemical and biological attributes of the soil) is constantly getting degraded and has been the important concern for the scientists, environmentalists and the planners at the global level. There have been advancements in this direction to identify and quantify the different soil attributes that can be easily determined in order to evaluate soil health/quality. The primary aim is the management of soil resources as per the need and their rejuvenation through best practices in hand.

But, most of these assessments contain the information of soil chemical parameters and nutrient levels only and provides no information on soil physical parameters, despite the fact that most of the criteria for healthy soils depends upon physical properties. In India, efforts are lacking in this direction where soil health cards are till now based on soil chemical properties and mostly used for fertilizer management.

Soil physical properties as indicators of soil health/quality: As stated above, productive soils have attributes that promote root growth; accept, hold, and supply water; promote optimum gas exchange; and accept, hold, and release carbon. All of these attributes are, in part, a function of soil physical properties / processes. Some of them are static in time, and some are dynamic over time scales. Some are resistant to change by agricultural management practices, while some are changed easily in positive and negative ways. A list of physical indicators that has been proposed by various researchers include soil texture, soil depth and rooting depth, bulk density, soil porosity and pore size distribution, plant available water content (PAWC), penetration resistance, saturated hydraulic conductivity, soil structure, aggregate size and stability, field infiltrability, organic carbon, soil surface cover etc. and these indicators may be part of soil quality assessment as per the need and site condition. However, these indicators must qualify the established criteria. Higher the number of criteria an indicator qualifies more are its suitability for including in minimum data set (MDS) required in explaining soil health. For example, soil organic matter (SOM) is a widely used indicator, because it can provide information about a wide range of properties such as soil fertility, soil structure, soil stability, and nutrient retention. That is why residue retention/ addition is prime focus in sustainable agriculture.

Soil resistance/ resilience: Although there are many indicators that reflect the current capacity of the soil to function, there are few that can predict whether or not the soil will maintain this capacity following disturbance. The capacity of a soil to continue to support the same potential range of uses in the future that it supports today depends on both its resistance to degradation and on its resilience. Soil processes, such as decomposition, mineralization, and macro pore formation are difficult and costly to measure. However, the properties on which these processes depend can often be quantified more cheaply and easily. For example, in many systems, recovery following compaction is related to earthworm density and species composition.

Advances Made in Measurement Techniques

Technological and methodological advancement is a key in improving our understanding of soil physical processes and a prerequisite for successful testing of hypotheses. Hypothesis-driven soil physical principles need access to high-quality data with the best possible temporal and spatial resolution to testify the hypotheses. Advances in measurements techniques like, tension infiltrometer, disc permeameter, time/ frequency domain reflectrometry with continuous and real time measurement of profile moisture content improved our understanding of soil hydrologic processes in micro and macro scales. TDR or capacitance based instruments along with temperature sensor simultaneously and continuously measure profile water content, temperature changes and soil salinity which is being used for irrigation scheduling and soil salinity management. Recent advancements in computer and digital technology have dramatically improved the ability to collect, process, and analyze penetrometer data. Digital data loggers, GPS and depth measurement devices have enabled the real-time association of raw data output with depth of penetration and calibration factors. The result is that soil properties can be measured with an estimated error and mapped in the field. It is also possible to predict soil bulk density, texture, and moisture in the field without taking a sample from penetration data. The digital penetrometer and GPS data can be integrated into a geographic information system (GIS) as well as statistically driven sampling routines to facilitate efficient and interactive on-the-fly mapping of soil attributes (Rooney and Lowery, 2000).

Besides this, advances in experimental methods and designs are required to provide data that can be used to effectively reduce uncertainty about the conceptualization and parameterization of root water uptake processes. At the smallest scale, tomographic techniques that operate at the soil column scale, such as X-ray CT tomography (*Carminati et al*., 2010) and microtomography (*Aravena et al*., 2011), neutron tomography (*Oswald et al*., 2008; *Carminati et al.*, 2010, *Moradi et al*., 2009), and nuclear magnetic resonance imaging (*Pohlmeier et al*., 2013), are very useful. These techniques could measure the impact of roots on rhizosphere properties (compaction and wettability) and demonstrate the effect of these properties on root water uptake.

For achieving higher water use efficiency it is important that appropriate quantity of water is applied at the right time. This will not only ensure the sustainable use of the limited available safe water supplies in many regions of the country but would also reflect in the safe and judicious use of costly inputs like fertilizers and high quality seed. Various remote and ground based technologies like thermal sensing for plant water status have been developed in the recent past for the measurement of plant water stress. In recent decades, infrared thermometry and infrared thermal imaging have come as good tools for detecting stomata closure and indirectly assessing plant water status. These techniques are of great use for rapid estimation of plant water stress and for scheduling of irrigation based on the temperature based algorithm to improve the use efficiency of water and also for higher productivity.

Remote sensing technologies have advanced significantly over the past 10 to 15 years. With the development of hyper spectral remote sensing technologies, researchers have benefited from significant improvements in the spectral and spatial properties of the data, allowing for more detailed plant and environmental studies. Advances in spectrometry have also resulted in state-of-the-art portable field instruments which allow for the collection of hand-held hyper spectral signatures.

Plant water content at the leaf and canopy scales could be estimated using specific spectral reflectance bands and spectral reflectance indices from near infrared, and short-wave infrared (SWIR) regions of the electromagnetic spectrum. NIR and MIR spectral bands are highly correlated to water content of vegetation and soils (Campbell *et al*., 2007). Detection of nutrient stress in plant at early stage is possible through the use of hyper spectral vegetation indices using hand held devices.

Similarly, the analysis and mapping of soil characteristics is also possible with hyper spectral and multispectral imaging. Maps of soil properties can improve precision agriculture technologies and enhance capabilities. Researchers were able to determine soil properties, even for soils under vegetation, with the use of hyper spectral sensors and MIR spectroscopy based soil reflectance analysis. The stratification of nutrients most commonly reported in fields under agriculture could be more easily identified using rapid measurement of soil properties using MIR and NIR spectroscopy techniques in combination.

Measurements of electromagnetic energy, that has either been reflected or emitted from the soil surface, through microwave remote sensing provides an all weather capability for measuring the spatial distribution of soil moisture content for regions with low to moderate levels of vegetation cover, but is limited to the top few centimeters of soil and to a revisit interval of once every few days. Recently launched NASA's Soil Moisture Active Passive (SMAP) mission is designed to monitor from space soil surface moisture content around the world in an effort to improve forecasts of hazards such as droughts and floods. This technique has great potential for estimation of soil moisture in areas under agriculture in association with profile moisture dynamics models for prediction of water balance of the system and improvement of water productivity.

The spatial configuration of soil, in its complexity, requires an understanding of the interrelations and interactions between the diverse soil constituents, at various levels of organization. Investigations of the spatial arrangement of the mineral and organic components of soil have benefited from the development of techniques for structural analysis. X-ray computed tomography (CT) is a non-destructive and non-invasive technique that has been successfully used for three-dimensional (3D) examination of soil. Valuable information could be obtained by the application of CT for the description and quantitative measurements of soil structure elements, especially of soil pores and pore network features. Tiana et al. (2008) observed that in agriculture the X-ray CT can be used to investigate the hydro-physical characteristics of the soil, in a functional and temporal manner.

Conclusions

In the back drop of advancements in soil science, the raising of input use efficiency for sustained productivity is a necessity of Indian agriculture because of the dwindling soil and water resources, declining soil health and rising cost of inputs making agriculture less remunerative. It is high time that we make judicious use of limited available quantity of safe water which is becoming scarcer and scarcer with time. Enhancing crop productivity with higher input use efficiency without any damage to the soil and water resources is thus a big challenge of Indian agriculture. Soil is a complex system which retains and transports water, plant nutrients and other chemicals from one layer of the soil to the other in response to hydraulic and concentration gradients. This provides nutrition to the plant roots and water to meet out the evapotranspiration demand. This differs from soil to soil owing to their characteristics. These characteristics play an important role and it is important that before developing any technology for the judicious use of inputs, the soil physical processes including soil-water-plant relations are well understood so as to realize the impact of management practices which may alter the soil physical, chemical and biological properties. In the recent past various advancements made to understand the soil physical processes including development of different models have made it handy to solve many problems related to complex and dynamic soil-water-nutrient-plant system. Also, techniques have been developed for rapid and precise estimation of various kinds of abiotic stresses which have a bearing on plant growth, grain yield and judicious use of various inputs in agriculture in order to arrive at sustainable practices of agriculture. However, our knowledge on the subject is limited because of complex nature and reconsolidation of soil system/structure owing to different management practices. There is more need to study this dynamic system in-depth in multidisciplinary mode, including the root system architecture with respect to water and nutrient uptake and mitigation of various kinds of plant abiotic and biotic stresses.

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