Advancing Soil Physics for Securing Food, Water, Soil and Ecosystem Services

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Soils are foundational to sustaining the food, energy, and water (FEW) systems and provide many essential ecosystem services. Soil degradation is a major threat to food security in China and elsewhere in the world. It is critical to advance soil science to improve the FEW systems so that FEW supplies can be provided to human populations in a sustainable and resilient manner. To do so, we must understand interactions among soil physical, chemical, and biological processes, as well as the role, function, and contribution of soil physical processes to delivering FEW supplies and ecosystem services. Soil processes and crop production are strongly controlled by physical processes such as soil water flow, aggregate stability, compaction, heat regime, irrigation and drainage, soil aeration, etc. Recognizing the importance of soil physics to the nexus of FEW systems, the collection in this special section mainly includes research presented at the International Workshop of Soil Physics and the Nexus of Food, Energy, and Water held on 3–5 Aug. 2017 at Shenyang, China. This special section covers diverse topics including fundamental soil physical properties and water flow, land use and agricultural management, soil organic carbon management, soil physical modeling, and transport of emerging contaminants. More future research using interdisciplinary (nexus or convergence) approaches should be undertaken to address challenges in many contemporary and emerging FEW issues.

Abbreviations: FEW, food, energy, and water; SOC, soil organic carbon.

Humanity is facing grand challenges to sustainably meet the needs of food, energy, and water (FEW) supplies for the rising world population estimated to reach 9 billion by 2050 (Hatfield et al., 2017; Lal, 2015; Liu et al., 2018). Provisioning of FEW supplies in a sustainable and resilient manner is foundational to human wellbeing and to achieving the UN’s Sustainable Development Goals (Liu et al., 2018). It is now well recognized that FEW systems are interdependent complex systems in nexus, and balancing FEW systems for social good requires interdisciplinary (or convergence) approaches (Liu et al., 2018). Soil is one of the most fundamental resources for life on our planet because it sustains our FEW systems and provides many essential ecosystem services such as provisioning services (e.g., FEW supplies), regulatory services (regulating greenhouse gas emissions, carbon sequestration, water quantity and quality, soil-borne pests and disease, soil erosion, natural hazards control, etc.), and supporting services (providing habitat, nutrient cycling, and biodiversity) (Amundson et al., 2015; Hatfield et al., 2017). Thus, the importance of soil resources in the nexus of FEW systems cannot be overstated but may have been either assumed or overlooked, which impedes the awareness and investment of the public in soil conservation and the translation of soil science discovery to policy actions (Hatfield et al., 2017). This situation is particularly alarming at a time when soil degradation has become an imminent global issue (Bai et al., 2008; Lal, 2015). Increasing demands on food and bioenergy production will place tremendous stress on soil and water resources in a changing climate, warranting basic science advances, proper land management, and innovative agricultural practices.

With accelerating industrialization and urbanization in China, resource stress (e.g., water shortage), environmental pollution, and soil and ecosystem degradation are becoming increasingly concerning (Jiang, 2009; Lu et al., 2015; Xie et al., 2014). It is a huge challenge to balance soil conservation, ecosystem services, and economic development in China and elsewhere in the world (Chen, 2007). For example, in China, soil pollution has...
grabbed the national spotlight as approximately 19% of sampled agricultural soils are contaminated (primarily heavy metals and metalloids) (Chen et al., 2015; Zhao et al., 2015). Soil pollution can lead to contamination of food crops and consequently an adverse impact on public health (Chen et al., 2015; Lu et al., 2015). China is also experiencing more severe cropland loss, increasing from a rate of 0.26 Mha yr$^{-1}$ in 1978 to 1999 to a rate of 1.45 Mha yr$^{-1}$ in 2000 to 2005 (Ye and Van Ranst, 2009), largely due to rapid urbanization (Chen, 2007). Soil degradation can threaten China’s long-term food security (Ye and Van Ranst, 2009).

In addition, water scarcity in China is accelerating, resulting from uneven spatial distribution and water pollution (Jiang, 2009). Both conventional contaminants (such as heavy metals and excess nutrients) and emerging contaminants (e.g., pharmaceuticals and antibiotic resistance genes) are contributors to water pollution in China (Li et al., 2018a; Lu et al., 2015; Luo et al., 2010; Zhang et al., 2015). Nitrogen and phosphorus losses from agricultural soils are also major drivers of eutrophication in China’s surface waters (Le et al., 2010; Qin et al., 2007). Water scarcity can profoundly impact food security, trade, and human health in China (Hong and Zehnder, 2001; Zhao et al., 2005; Lu et al., 2015; Yang et al., 2003). Therefore, more effort needs to be devoted to science-based and sustainable management of soil resources in the context of the FEW nexus.

Because fundamental physical, chemical, and biological properties and processes in soils determine soil functions and ecosystem services (Hatfield et al., 2017), it is important to advance soil science to secure the FEW supplies and ecosystem services that soils provide. Chemical and biological processes in soils must operate within the boundaries of the soil physical environment. We must understand interactions among soil processes, as well as the role, function, and contribution of soil physical processes to delivering FEW supplies and ecosystem services. Soil physics is indispensable to understanding biogeochemical cycles and nutrient cycling in natural and managed ecosystems (e.g., agroecosystems). For example, soil hydrology (including spatiotemporal variations of moisture and water flow in soils) controls N and C cycling by regulating redox conditions, plant uptake, and transport of N and C across space and time in the landscape (Keiluweit et al., 2017; Zhu et al., 2018a). Soil temperature (especially the soil temperature threshold above which microbes become very active) is also known to play a critical role in ecosystem biogeochemistry (Cosentino et al., 2013; Smith, 2017). Other soil physical properties (including soil texture, structure, aggregate stability, bulk density, and compaction) can also affect crop productivity and biogeochemical cycling.

**State of Soil Physics Research**

Advances in soil physics have recently been made to address the grand challenges of ensuring sustainable FEW supplies, maintaining valuable ecosystem services, and protecting environmental and human health. Advanced modeling and monitoring tools are being developed. Direct field and laboratory measurements and remote sensing are typically used to measure soil physical properties across a multitude of temporal and spatial scales but often at restricted spatial and temporal resolutions due to cost constraint. Therefore, soil physical models and hydrogeophysical tools are increasingly used in place of direct measurements (Vereecken et al., 2015, 2016). For example, during the last decade, numerical models have been utilized to investigate soil hydrological processes through scenario analyses (Fang et al., 2015; Lai et al., 2016). Hydrogeophysical tools such as electromagnetic induction, electrical resistivity tomography, and ground-penetrating radar have been used to probe subsurface processes and calibrate the numerical models (Guo and Lin, 2018; Vereecken et al., 2015).

Management of soil organic C (SOC) is being intensively studied because many essential ecosystem services including C sequestration, soil fertility, water retention, contaminant immobilization, and crop production are heavily regulated by the amount and distribution of SOC (Lal, 2004; Stockmann et al., 2015). Soil organic C also strongly controls soil physical properties such as soil aggregate stability, compaction, water retention, etc. Atmospheric CO$_2$ concentration and climate change are critically controlled by SOC, as a loss of 10% of the total SOC in the upper 1 m of soils (about 2500 Gt C) (Lal, 2008; Stockmann et al., 2013) is equivalent to approximately 30 yr of anthropogenic C emissions (8.6 Gt yr$^{-1}$) (Kirschtebaum, 2000; Lal, 2008; Stockmann et al., 2013). On average, 5% of the SOC in the upper 10 cm of soils was lost between 2001 and 2009 globally (Stockmann et al., 2015). A rapid decline in SOC levels will cause environmentally and economically dangerous soil degradation that threatens the sustainable FEW supplies and human wellbeing (Amundson et al., 2015; Lal, 2004).

Measurement of CO$_2$ emission is important to assessing SOC stability and its impact on climate change. In recent years, new sensors and measurement devices have been developed to enable the use of the gradient method (De Jong and Schappert, 1972; Maier and Schack-Kirchner, 2014; Sánchez-Cañete et al., 2017) for continuous gas flux measurements (Flechard et al., 2007; Hirano et al., 2003; Vargas et al., 2010). Also, as a SOC management practice, biochar amendment in soils is being promoted for many agro-nomic and environmental benefits (Jeffery et al., 2011; Kookana, 2010; Laird, 2008; Lehmann et al., 2006), e.g., improving soil physical and chemical quality (e.g., soil structure, bulk density, water storage, and nutrient retention), decreasing greenhouse gas emission, and immobilizing contaminants in situ (Beesley et al., 2011; Lehmann, 2007; Liu et al., 2016a; Wang et al., 2016). Nonetheless, conflicting results have also been reported regarding the impact of biochar amendment to soil physical properties, showing that biochars can either improve soil water retention (Eibisch et al., 2015; Herath et al., 2013) (thus alleviating the negative impacts of drought) or increase soil water repellency, thus reducing infiltration and increasing surface runoff (Jeffery et al., 2015). Additionally, biochar addition to soils may impact soil C cycling and cotransport of other contaminants sorbed to biochar colloids due to the release and transport of dissolved and colloidal biochar organic C (Chen et al., 2018; Liu et al., 2019; Wang et al., 2013a,
Soil physics research is instrumental to developing proper land use and agricultural practices. For example, in arid and semi-arid regions (e.g., the Loess Plateau in China), film mulching is a common practice that improves crop yield by augmenting water use efficiency and soil temperature (Deng et al., 2006; Liu et al., 2016b). The Loess Plateau is also facing challenging problems of low soil fertility, water shortage, and slow economic growth, resulting in the implementation of orchard plantation (e.g., apple [Malus Mill. spp.] trees) as a solution. However, apple trees consume a large amount of water and therefore use most of the rainfall (Huang and Gallichand, 2006; Li, 2001; Wang and Wang, 2017). A dry soil layer is often formed in the soil profile, presenting a serious obstacle to sustainable land use (Shao et al., 2018b; Wang et al., 2011). Therefore, fundamental and applied soil physics research is imperative to sustainable agricultural production under challenging climatic and soil conditions in China and elsewhere.

An area of emerging importance is the study of the transport of emerging contaminants in soil, water, and plant systems. Emerging contaminants are not typically monitored or regulated and may cause potential adverse impacts to human and ecosystem health (Sauvé and Desrosiers, 2014). Attention to some emerging contaminants have recently intensified, including pharmaceuticals (such as antibiotics), antibiotic resistant bacteria and genes, engineered nanoparticles, etc. (Li et al., 2018a; Richardson and Ternes, 2014; Snow et al., 2012; Williams-Nguyen et al., 2016). Because knowledge of their environmental occurrence and impact is still insufficient, these emerging contaminants pose great scientific and regulatory challenges for mitigating their risks to agricultural production as well as human and ecosystem health (Richardson and Ternes, 2014; Sauvé and Desrosiers, 2014). Therefore, it is important to understand environmental processes and impacts of emerging contaminants and their transfer in the food chain (Bhalsod et al., 2018; Chuang et al., 2018; Li et al., 2018b) for scientifically informed risk assessment and management.

Finally, many soil ecosystems are critical zones (e.g., the Loess Plateau and the karst region in China) that are extreme, fragile, and/or sensitive to disturbances such as land use and climate change. These critical zones often overlap with intensive agricultural production areas. Therefore, advancing fundamental soil physics and developing science-based management practices in diverse physical settings are key to securing a sustainable future of FEW while protecting ecosystem services and responding to global environmental changes. Current practices of energy and food production can cause environmental pollution, water scarcity, and soil degradation, posing great challenges to regional and global sustainable development. We urgently need to understand and manage soil physical processes to develop better solutions for the accelerating FEW demands, while enhancing the resiliency of human societies to anthropogenic and natural stresses and hazards.

This Special Section

Recognizing the importance of soil physics to the nexus of FEW systems, the International Workshop of Soil Physics and the Nexus of Food, Energy, and Water was held on 3–5 Aug. 2017 at Shenyang, China. This special section primarily consists of work presented in the workshop, covering a range of topics including fundamental soil physical properties and water flow, land use and agricultural management, SOC management, soil physical modeling, and transport of emerging contaminants.

Soil Physical Properties and Water Flow

The characterization, measurement, and modeling of soil physical processes are the keys to better characterizing the ecosystem services of soils. Using laboratory experiments, Wang et al. (2018b) investigated water flow and finger flow formation in a sandy loam and a clay loam with varying water repellency. They observed that infiltration was lower and water flow was unstable at higher soil water repellency. Finger flow formation was more pronounced in the water-repellent sandy loam than in the water-repellent clay loam, which probably resulted from faster infiltration in the coarse-textured soil. At the field scale, Wang et al. (2018a) studied preferential flow in a small karst catchment in Guangxi Province in Southwest China. They observed that macro pore flow formed in karst depressions and downslope, finger flow formed in the middle- and up slope land, and the degree of preferential flow and infiltration rates may be independent from each other in the karst region. Through a rainfall manipulation experiment, Hess et al. (2018) observed that deep water percolation and deep soil water content were increased by rainfall intensification for both tilled and no-till cropping systems. At the regional scale, using a neutron probe to determine the soil water content in the 0–5-m soil depth across a 500-km transect in the Loess Plateau of China, Zhao et al. (2018) found that soil water content was controlled by varying environmental factors at different spatial scales (i.e., precipitation and temperature at large scales of >250 km, elevation and sand content at moderate scales of 65 km, and clay content at all scales). By imaging intact soil cores with computed microtomography, and measuring the soil water retention curve, mean weight diameter, and mass fractal dimension, Cui et al. (2018) assessed changes in the pore network and aggregate stability of soils under inundation and water level fluctuation in the Three Gorges Reservoir region in China. They observed decreases in the number of soil pores and total soil porosity, and a shift from drainable micropores with radii between 0.1 and 125 μm to non-drainable micropores with radii <0.1 μm, as a result of soil inundation. Liao et al. (2018) also developed a simple and improved model to describe soil hydraulic properties from saturation to oven dryness, which has the potential to be used in vadose zone transport models.

Land Use and Agricultural Management

The demands on land for crop and bioenergy production is increasing. Thus, marginal land and/or degraded land need to be
properly managed or reclaimed for agriculture. Several papers in this special section address land use and management from a soil physical perspective. Using multiple regression techniques, Fei et al. (2018) studied the controlling factors on soil salinity and alkalinity in a reclaimed coastal area of the Yellow Sea located in Jiangsu Province, China. They found that land use pattern (farmland vs. fallow), vegetation coverage, reclamation history, and soil texture significantly affected the soil salt content and the sodium adsorption ratio. Hu et al. (2018b) found that soil physical quality (e.g., microporosity, available water content, and saturated conductivity) was significantly deteriorated by compaction from livestock treading. Tillage could temporarily improve the soil physical quality in the compacted soils.

Regarding agricultural management, increasing water use efficiency and soil temperature can help small farmers achieve a stable and high maize (Zea mays L.) yield in the rainfed area of Northeast China. Sun et al. (2018) found that soil water storage was significantly increased by plastic film mulching. Transparent film mulching resulted in a higher soil temperature than black film mulching. The root length, root length density, and root diameter of maize were increased by plastic mulching. At the heading stage of maize, higher soil temperature resulted in better growth of the maize main root, but the final yield was lower. Wang and Wang (2018) studied the relationships between the age of trees and soil water dynamics in young (7-yr) and old (17-yr) apple orchards on the Loess Plateau. They concluded that (i) mean soil water content, soil water storage, and available soil water were consistently higher in the 7-yr-old orchard, (ii) a dry soil layer was formed in the deep soil depth in the 17-yr-old orchard but was absent in the 7-yr-old orchard, and (iii) tree age should be considered when developing water management strategies for apple orchards on the Loess Plateau and in similar semiarid environments.

**Soil Organic Carbon Management**

In this special section, Zhang et al. (2018a) studied the spatiotemporal variability of SOC in cropland in Henan Province, China. They found that fixed C was the greatest in Inceptisols and the lowest in Anthrosols and that there was an increasing trend in SOC from 1981 to 2011. Thus, they hypothesized that properly managed cropland may have a great potential for C sequestration. They called for more attention to crop residue incorporation into soils because it has potential to increase SOC and crop productivity within a short period. Chen et al. (2018) investigated the effect of biochar amendment on hydraulic properties of sandy soil under dry and wet conditions and found that water retention of the sandy soil was increased by biochar amendment under saturated and dry conditions but decreased at field capacity. The evaporation rate under dry conditions also decreased with increasing biochar amendment rate, biochar particle size, and pyrolysis temperature.

Improving the accuracy of soil CO₂ efflux measurements is key to accurately assessing the impact of SOC on climate change. To examine the effect of the soil water dynamics of different soil textures on CO₂ emissions, Yang et al. (2018) applied the gradient method in soils with three different textures (loam, silty loam, and silty clay loam) using packed soil cores under alternating wetting-drying cycles. Carbon dioxide production in the loam soil and CO₂ production and gas diffusion in the silty loam soil were main factors that affect the CO₂ efflux. Wang et al. (2018c) designed a portable canopy chamber to determine crop CO₂ exchange rates at a relatively small spatial (m²) scale, applied it to measure CO₂ fluxes in corn and soybean [Glycine max (L.) Merr.], and demonstrated the usefulness of this method by comparison with adjacent eddy covariance flux tower measurements.

**Soil Physical Modeling**

Modeling is useful for prediction, scenario analyses, or elucidating mechanisms in soil water management, crop production, and environmental protection. Soil hydrological modeling is instrumental to soil water and crop management in the Loess Plateau of China. Using the HYDRUS-1D model, Zhu et al. (2018b) investigated water stress during two maize growing seasons on the Loess Plateau. In the early stage of the maize growing season, pre-seeding soil water storage can effectively alleviate crop water stress. The HYDRUS-1D simulation showed that the plow pan at a depth of 20 to 40 cm was the sensitive layer for water stress during the drought period. Effective management practices such as deep plowing, plastic film mulching, or water conservation treatments during the fallow period were needed to avoid the formation of this temporary dry layer during the drought period at the early stage and to improve maize production in rainfed agriculture on the Loess Plateau.

Using field data and modeling with the Community Land Model, Shao et al. (2018a) showed that on the Loess Plateau over a period of 115 yr, deep soil water recharge (e.g., >75-m depth) would occur in wet years with a precipitation >650 mm yr⁻¹, and groundwater recharge mainly depends on the frequency of wet years rather on the average annual precipitation. Hu et al. (2018a) assessed the potential impact of reclaimed water discharge to rivers and subsequent leakage to groundwater on the quality of groundwater (NH₄⁺, NO₃⁻, and Cl⁻). They reported that geomembrane liners can be an effective control for leakage from the river, thus helping to prevent contamination of the groundwater by contaminated surface water.

**Emerging Contaminants**

Zhang et al. (2018b) investigated the transport of sheet-like graphene oxide nanoparticles in saturated sand and found that increasing the flow velocity actually increased the attachment efficiency of the graphene oxide nanoparticles on rough sand surfaces, in contrast to typical observations with other types of colloids. More research should be directed to this area because it is of emerging importance to food and water security as well as human and ecosystem health.

**Concluding Remarks**

This special section includes a range of work covering various aspects of soil physical processes in controlling FEW systems and ecosystem services. More research should be devoted to energy flow...
in soils, energy consumption in agricultural production, and bioenergy production as influenced by soil physical processes. Regarding SOC management, future studies should be directed to physical controls of the soil microbiome and its function in soil C dynamics. Efforts should be also made to elucidate the role of plants in soil water flow using advanced in situ characterization techniques for

Finally, to ensure that soils provide critical functions to FEW systems and ecosystem services, interdisciplinary research intersecting soil physics, chemistry, biology, and social science is needed. This area should be strengthened in the future, as most studies in FEW problems across multiple scales and heterogeneous domains. Integration of physical, chemical, and biological processes in model development is also needed to address critical FEW problems across multiple scales and heterogeneous domains.

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