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FUTURE DIRECTIONS IN SOIL SCIENCE AND ECOSYSTEM MANAGEMENT

Abstract

The field of soil science stands at the crucial juncture driven by a confluence of global challenges such as climate change, land degradation, biodiversity loss, increasing population and demand of food and fuel. Soil science is currently evolving as numerous advancements unfold in technology such as remote-sensing and nanotechnology which will widen our scope to study soil properties and processes from different perspectives. The integration of data science models and machine learning holds promise for predictive soil mapping helping in making efficient land use decisions without compromising on time. Moreover, consideration of inter- and trans-disciplinary approaches to emphasize interconnectedness of soils with climate, hydrology, microbiology, computer science and engineering. Ecosystem management is undergoing paradigm shift towards more holistic adaptive and mitigation strategies to restore and conserve degraded ecosystems. As the reach of soil science keeps on growing every day, coordinated efforts from across the globe are required to face the global issues related to climate change and biomass degradation. However, integration of traditional knowledge systems and modern scientific approaches needs due regard in the wake of upcoming global trends.

Keywords: Ecosystem services, climate change, sustainable management, conservation agriculture, nanotechnology

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I. INTRODUCTION

Soils, as any other economic good, can be considered as a natural capital due to its role in provisioning of ecosystem services (ES). An ES is a result of various soil functions working in conjunction with other components in earth's atmosphere to deliver something substantial to humanity as a consequence of complex relationship between living organisms and their non-living counterparts. The ES can be categorized into cultural, provisioning, regulating and supporting services. Provisioning services can be regarded as products obtained from any ecosystem that have a market value such as food, feed, fiber, fuel etc. Regulating services are the gains obtained from regulation of ecosystem functions such as floods, climate and diseases. Supporting services work as supplementary help to major ecosystem services such as water and nutrient cycling, biomass production, soil formation and retention etc. Cultural services are the intangible benefits gained by people such as aesthetic experience, recreational development, spiritual enrichment etc.

Soils share the interface with lithosphere, atmosphere, hydrosphere and biosphere therefore, forms an inseparable component of different ecosystems which makes it mandatory to study them through inter- and trans- disciplinary approaches. Soil is a home to gigantic biodiversity that regulates the majority of ecosystem processes in varied landscapes laying the stepping stone for our day-to-day activities. Soils are the source of plants, raw material for industrial and pharmaceutical uses and food production regulated by ecosystem functioning. Existence of soils is entirely dependent on its use by humans and thus, it is a conditionally renewable resource whose contribution to ES decides its suitable management. Unfortunately, soils have recently come under major environmental threats as a consequence of climate change and human pressure, endangering food safety for coming generations. Balance of soil-water-air-plant continuums may be thrown off track by decreasing fertility as observed with increase in greenhouse gas emissions. Additionally, being the largest terrestrial carbon sink, soils can quickly turn to a source of GHGs if handled injudiciously. In this era of agricultural outgrowth, unsustainable practices have become prevalent accelerating soil degradation processes at an uncontrolled rate with negative impact on soil value. The faulty agricultural practices can dampen soil biota, microbial biomass and carbon and escalate problems like soil compaction, acidification, erosion and salinization. Soil ES of provision, regulating and cultural value are specially threatened in areas that are intensively managed and more sustainable approaches are needed to reduce soil ES degradation. Restoration of degraded ecosystems can rejuvenate soil's contribution to ES.

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II. ROLE OF SOILS IN ACHIEVING SDGS

The UN sustainable development goals, formulated in 2015, aim to work towards sustainability of natural resource use, zero hunger, equality and proper education for all. The achievement of most of the SDGs requires proper functioning of soil-water systems. Some SDGs are directly dependent on soils while others have an indirect relation. For example, SDG 2 targets to end hunger and achieve food security with improvement in nutritional status of food crops to promote sustainable agriculture. This not only falls under the premises of agronomic studies but also touches social, economic and political aspects. Most of this is attainable by cooperation among at least 20 other disciplines. Human health and well-being for all age groups is ensured under SDG 3 which again requires help from soil scientists to manage fertilizer sources and nutrient management. SDG 6 works for sustainable management of water and proper sanitation for all. Soils act a filter to various pollutants and toxic substances as a service to the ecosystem. SDG 13 focuses on taking urgent action to combat climate change and its impacts. Agriculture being one of the contributors of greenhouse gases (GHGs) has a role to dampen down the release of GHGs with proper mitigation practices. Lastly, SDG 15 addresses the need to protect, restore and promote sustainable use of terrestrial ecosystems, forest management, combat of desertification and reversing land degradation to stop biodiversity loss. The first step in the attaining of SDGs would be to gather soil scientists to work on soil-water-plant-atmosphere (SWAP) model, enlisting soil functions that contribute to ecosystem services and for an interdisciplinary approach towards it.

Soils ES are at the center of nutrient cycling, buffering of pollutants, food production and poverty alleviation. The amount and quality of the ES provided by soils are dependent on the soil genesis, initial material, topography, organisms, and climate. Provisioning services function to ensure food, fiber, wood and raw materials to the humankind. These services are a result of soil biota that are labeled as “ecosystem engineers” involved in pedogenic processing to develop key soil properties important for mineralization of organic matter, biogeochemical cycling of nutrients, structural development and biomass production. Regulation of soil ES sustains forest, agricultural and urban ecosystems. Forests offer a vast range of services such as food products (fruits and berries), timber, medicinal plants, oxygen and water which are directly or indirectly derived through soils. In return, they act as soil cover anchoring and protecting soils against erosion by wind or water and sequestering carbon through addition of leaf litter.

It can be aptly said that food production begins in the soil as it provides environment for seed germination, root growth, support to the roots, and provision of nutrients and organic matter released in plant-available forms. Various nutrient transformations happen in the soil matrix through biological, chemical and physical processes for crop uptake and release. Soil also serves as a habitat for soil biota which may form beneficial or harmful connections with plants growing in them. It also forms the platform for movement of farm traffic, humans and animals and forms the foundation for various social plans like construction of roads, dams, buildings etc. Bringing land under agricultural management changes soil properties (soil pH, structure, organic matter content etc.) often against that required for optimum ecosystem functioning raising conflicts between designated functions of soil for food production. In search of methods to maximize food production to sustain exploding population, humankind has always overlooked the long-term consequences to the environmental health but academicians are now shifting gears to interlink food availability with ecosystem services.

III. HURDLES IN ACHIEVING SUSTAINABLE FOOD PRODUCTION: A SOIL'S PERSPECTIVE

Degradation of soil as a natural resource occurs as a consequence of interconnected factors such as climate-biota interactions, bio-physical and socio-economic interactions and anthropogenic and natural disturbances. Soil degradation can directly affect human nutrition because of the fact that decrease in soil quality deteriorates amount and quality of agricultural output (IRP 2019). Loss of soil organic matter (SOM) is one of the most important reasons behind decrease in soil biodiversity. The risk of such loss arises from inappropriate land management practices, denudation of fertile top soil through over grazing, land-clearing and forest fires. Moreover, soil salinity developed as a result of overuse of poor-quality irrigation waters and improper drainage conditions are some other reasons of soil degradation. Urbanization and rapid expansion of cities will result in competitive use of natural resources such as land which will severely impact security of food to coming generations. The need to feed an ever-increasing population will degrade the soil's capability to sustain crop productivity. The land use change will cause shift in farm fields from semi-urban through rural to marginal lands. This will also put a pressure on the use of irrigation water resources lowering water table which will limit crop production and alternate agricultural options.

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Moreover, global issue of rise in atmospheric temperatures from increased GHG emissions further complicates the problem at hand. Rise in temperature may alter phenology of crops, reduce pollen germination, increase respiration rates, and reduce duration of grain filling ultimately lowering crop biomass and yields (Ahmed *et al*., 2018). Major food crops such as wheat, rice, maize, and soybean accounting for more than 67% of human calorie intake are now under the threat of global warming. It is estimated that 1°C rise in temperature will bring the global production of wheat down by an average of 6%, rice by 3%, maize by 7.4% and soybean by 3.1% (Zhao *et al*., 2017). Out of all the crops, sorghum is expected to be least impacted with yields varying within 5% of the current production. Other crops that will be less affected are root crops, including sweet potato, potato, and cassava, whose yields could range from 15% to 10%. Rise in temperature may accelerate the biomass production on one hand and decelerate the accumulation of SOC due to improved microbial decomposition on the other hand (Keestrea *et al*., 2016). The experimental findings suggest the presence of positive land-carbon feedback that can hasten climate change due to net loss of soil carbon to atmosphere with rising temperatures (Crowther *et al*., 2016).

Soil contamination by the presence of excessive amounts of heavy metals, agrochemical residues, industrial effluents and urban wastes in agricultural soils obstructs the degradation of soil organic matter, hinders microbial activity and thus, alters nutrient cycling lowering soil fertility and crop yields. The pollutants move up the food chain and magnify in amounts on attaining higher trophic levels becoming a major cause of animal deaths including humans. Contamination of soil can also occur due to the use of poor-quality irrigation water. It has now become imperative to bring municipal sewage and industrial wastes under consideration for agricultural purposes. Use of reclaimed wastewaters is getting attention among areas having substandard quality of groundwater. Salinization of soil is a form of land degradation causing nutritional imbalances and ion toxicities to impede plant growth and thus crop yields. Though the issues are numerous, generating proper framework to find solutions should be our first priority.

Climate change is a common issue among academicians, politicians and the humankind. To simplify this term, different perspectives can be taken into account. Some consider global warming as climate change which is not entirely wrong but requires more in-depth definition from a scientific point of view. The global CO_2 levels in atmosphere have been on an increasing trend over the past few years under different scenarios. An assessment shows that under business as usual scenario, CO_2 levels have seen a rising trend from 1900 and may exceed 700 ppm mark by the end of 21^{st} century. CO_2 has a key role to play in photosynthesis and stomatal conductance, thus having marked effect on crop yields by forming a basis for fertilization (Attavanich and McCarl, 2014; Long *et al.*, 2005; McGrath and Lobell, 2013). The rise in CO_2 to 550 ppm by mid-21^{st} century will increase photosynthetic activity of C3 plants (rice, soybeans, and wheat) by 38%. C3 plants are benefitted by increased levels of CO_2 in the form of increased carbon absorption, decreased photorespiration and enhanced water use efficiency (McGrath and Lobell, 2013). The C4 plants have no direct benefit from CO_2 enrichment but rather exploit increased water use efficiency, greater intercellular CO_2 and lowered stomatal conductance to their advantage in the form of improved productivity (Leakey, 2009). In this case, world will see an increase in yields of maize, soybeans, rice, and wheat by 7%, 24%, 16%, and 17.5%, respectively, by 2080s (Parry *et al.*, 2004). Though the elevated CO_2 will safeguard plants against abiotic stresses, the detrimental effects of high temperature or light intensity on the reproductive process are not likely to be restored.

IV. CLIMATE CHANGE MITIGATION WITH ADAPTATIONS TO FOOD SECURITY

Adaptation and mitigation are the two options to guard food security against changing climate. Agricultural adaptations may include practices like adjustment in planting dates, managing post-harvest storage, selecting adaptable cultivars, judicious input use and water harvesting (Descheemaeker *et al.*, 2016; Hasan *et al.*, 2018; Hasan and Kumar, 2019). Another effective adaptation would be crop diversification (Rojas-Downing *et al.*, 2017) and building on-farm biodiversity to sustain crop productivity. Small-scale farmers can benefit from introduction of weather-index crop insurance schemes in developing countries (Greatrex *et al.*, 2015). Adaptations are the best options to tackle climate change but potential of following mitigation practices can be still explored (Gopalakrishnan *et al.*, 2019). Agroforestry, organic farming, and sustainable land management form some of these practices. A profitable venture for farmers would include the practice of agroforestry with leguminous fodder crops, intercropping or following region specific crop rotations, and mechanization of farm practices for cultivation and crop residue retention/incorporation contributing to all three pillars of climate-smart agriculture, namely mitigation, adaptation, and food security (Descheemaeker *et al.*, 2016; Loboguerrero *et al.*, 2019).

Organic farming is another form of crop production to sequester carbon into the soil. It offsets the demand for synthetic fertilizers which considered as environment polluters and root cause of NO_2, CO_2, and CH_4 emissions in agriculture (IPCC, 2014; Wysocka-Czubaszek *et al.*, 2018). It allows for the re-use and recycling of farm waste reducing carbon footprint in farming. Working towards sustainable land management as an adaptation and mitigation strategy will not only reduce or reverse land degradation but also will increase carbon storage enhancing agricultural productivity and claiming food security for future generations. Grazing management can minimize soil erosion and nutrient loss by increasing soil cover, residue retention and following conservation tillage (IPCC, 2019). Bringing changes in dietary patterns and limiting food wastage has a potential to decrease carbon footprints by three gigatonnes of CO_2 equivalents (Gt eCO_2) by 2030 (Dickie *et al.*, 2014). In advocating the adoption of recommended adaptation and mitigation measures to farmers, there seem to be some socio-economic, agro-ecological, financial and political barriers (Ojiem *et al.*, 2006). Farmers face lack of effective extension services, weak community structure, inefficient supply chains and market infrastructure, high-rated farm inputs, land tenancy and exploitation which explains some of the barriers in adoption of alternatives by farmers (Descheemaeker *et al.*, 2016; Wiebe *et al.*, 2019). Policy and institution level formulation of framework is beyond the control of farmers however, the institutional setup can be updated for small scale farmers (Aryal *et al.*, 2019). Current suggested adaptation and mitigation options may not be able to withstand climatic aberrations in the wake of rising global food demand. In this regard, breeding for high-yielding, abiotic- and biotic- stress tolerant and nutritionally rich crop varieties can provide for growing demand of food production and food security globally (Qaim, 2020). Research and governance should engage all possible stakeholders, such as communities, organizations, and government.

V. FUTURE LINE OF WORK FOR SUSTAINING SOIL PRODUCTIVITY

Soil is at the junction of atmosphere, lithosphere, hydrosphere and biosphere that remains critical to sustainability to food production and functioning of ecosystem services. The concept of soil health got introduced late back in 2000s which now is unified under the flagship term of “One Health concept”, in which the health of animals, humans and environment are interconnected. Similar terms include soil fertility, soil quality and soil security. Soil fertility is the core term referring to the role of soil in crop production which can be manipulated by framer practices followed at the field level. Soil health falling under the term soil quality revolves around the ability of the soil to function in context to its immediate environment. Soil quality dictates the quality of water, animal and human health in the entire ecosystem. All these terms are now being used interchangeably despite having some fine distinctions. The term soil security, introduced in 2012, encompasses previously existing terms to describe the management factor of soil with the term 'soil condition'. It relates soil ES at the same level to human rights often in context of human culture, capital and legal management.

The sequestration of SOC has become part of the global carbon agenda for climate change mitigation and adaptation through the launch of the "4 per mile" initiative at COP21 by UNFCC in Paris in 2015. The idea behind the initiative is that an annual increase of 4% of the global SOC stocks in the top 0.3 to 0.4m of all non-permafrost soils would counteract the annual global rise in atmospheric CO_2. Loss of SOC is accelerated by lower input from aboveground and belowground biomass of crops and hastening of SOC decomposition by tillage practices through microbial degradation. Another reason for SOC loss can be relocation of C input within 20-30 cm of soil depth. Moreover, erosion by water or wind takes away the fertile top soil rich in OM. Soil can benefit from long term application of well decomposed manures to replenish the labile and non-labile SOC pools in soils. However, application of such manures often requires supplementary addition of N fertilizers due to immobilization of N in initial stages of decomposition of manures.

Conservation tillage has ample amount of benefits for soils in the form of residue incorporation and residue retention from reduced and no-till farming practices in the long-run. The positive effects are however, evident only in the surface layer (0-15 cm) and more specifically confined to 0-5 cm of top soil surface. No till systems are limited by depth to which SOC sequestration occurs and also by increased nitrous oxide emissions at start of the practice. However, the positive effects surpass the differences in soil C sequestration potential among different tillage practices. Cover cropping and crop rotations have similar effects on sequestering SOC along with provision of other valuable ecosystem services such as increase in water infiltration, nutrient retention, microbial activity, smothering of weeds and reduced need of external input of fertilizers. Cover cropping reduces the dependency on external N inputs by increasing N use efficiency through improved N mineralization and enhanced microbial biomass as studied in various studies (Sarrantonio *et al.*, 1994; Herridge *et al.*, 2008). Sequestration of carbon in soil comes with a price as it also immobilizes N present in SOC which requires excess of N inputs needed to

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compensate for plant uptake. Moreover, N immobilization can cause trade-offs with nitrous oxide (N_2O) emissions. Thus, the challenge lies in bridging the yield gap along with management of N_2O emissions to contribute to climate change mitigation. This demands improvement in N use efficiency with low N_2O emissions in soils with low C sequestration potential.

Nanotechnology is an upcoming field in area of soil science research which is a platform bringing together sciences like physics, chemistry, biology and engineering. Nanotechnlogy finds in its application in nutrient supply, pesticide application, insect repellants, nanosensors, nano-magnets, nanofilters etc. Nanoparticles constructed through different approaches have a size range of 1-100 nm. Nanoparticles possess unique physicochemical and biological properties as compared to conventional used in agricultural studies. However, they also pose threat to human and soil health. The engineered nanomaterials are released at various stages of its synthesis, usage and final disposal of these products. These nanomaterials may end up in soils during usage and disposal phases as they degrade faster in landfills going in streams by leaching. Thus, their residence time in soil need to be studied in context to physicochemical and biological properties of soil such as ionic composition, soil pH, temperature, etc. in depth before their recommendation to field application.

Soil maps can support and integrate many research areas such as pedology, soil classification, soil survey, land use planning, carbon sequestration, and environmental risk monitoring. DSM consists of three major components namely input data in the form of field and lab soil observations, the process of finding the best fit statistical models for studying soil-environment relations and output in the form of raster/thematic maps. With the advent of computer and information technology in the late 20th century, technologies like geographic information system (GIS), global positioning system (GPS), remote sensing (RS) and geostatistics, digital elevation models (DEM), light detection and ranging of laser imaging detection and ranging (LIDAR) and radio detection and ranging (RADAR) are receiving increased attention from soil science community. Further, the employment of proximity sensors such as portable X-ray fluorescence (PXRF) spectrometry, gamma-ray radiometry, UV-visible fluorescence spectrometry and visible near infrared reflectance (Vis-NIR) spectroscopy and statistical algorithms has opened unexplored horizons in area of soil science research. The Global Soil Map program aims to provide a global map of harmonized soil profile characteristics based on international standards. The future lies in the availability of high-priced satellite imagery for extraction of meaningful relationship between map features and in-field measurement of soil properties. This would allow for the wider coverage of agrarian areas on digital soil maps.

VI. CONCLUSION

Contribution of soils to ecosystem services should be linked to soil functions as each function is connected to ecosystem services to society with various degrees of success. This requires an inter- and transdisciplinary approach to study connections in relation to ecosystem services as biomass production is not only a function of soil but also dependent on crops or vegetation grown, the climatic variability, water availability, attack of pests and diseases, goals of production and also opinions of stakeholders involved. Soil scientists can help the soils recite their story and communicate it to the people as a "living" entity. Pedalogical studies of soils need to consider the impact of soil management on taxonomic classification of soils that is to shift focus from genoforms to phenoforms. This way soil maps of a given area can be studied from the viewpoint of management accounting for past land-use history. Linking soil functions with ecosystem services and connecting them successfully with needs and demands of stakeholders and policy makers can only be successful when continuing attention is given to interaction and co-learning processes. We need to focus on developing a two-way connection between soil scientists and land owners.

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