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Long term soil fertility management practices for nutritional security

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Abstract
Southern Asia's soils provide nearly 1.8 billion people with food, but are vulnerable to many sustainability problems. The ever-increasing population has placed tremendous pressure on the natural resources available (land/soil and water) that are threatening food security in the future. Urbanization is encroaching on the fertile farmlands. Declining groundwater levels, increasing micronutrient deficiencies, the use of fertile soil for brick making, degrading soil structure, and global warming are serious sustainability issues in Southern Asia. The extensive production of cereals and conventional soil management practices are increasing soil erosion; depleting soil organic matter, soil fertility, water resources, and increasing salinization. The restoration and management of soil organic matter, rainwater harvesting, and the efficient use of water and sustainable nutrient management are essential to sustain the long-term productivity of agricultural soils. Diversification of monocropping systems and the adoption of conservation agriculture may enhance the sequestration of soil carbon and increase biodiversity. However, site-specific technologies must be identified and made available to farmers. Prime agricultural land must be protected against urban encroachment. Communication and collaboration between scientists, farmers, and policymakers are needed to manage soils for ensuring food security in Southern Asia. The objective of this review is to deliberate the causes of soil degradation in Southern Asia and suggest soil management options to reverse the degradation trends and ensure long-term food security in the region.

Keywords: Soil degradation, conservation agriculture, water harvesting, crop diversification

1. Introduction
Southern Asia covers an area of 5.2 million square kilometers (11.71% of Asia) and includes Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. The region is endowed with diverse soil resources and great variation in climate and vegetation. Different food, fiber, sugar, and vegetable crops are grown on the diverse soil types in Southern Asia. Thus, sustainable soil management is necessary to ensure food security in this region.
Soil formation is a continuous and complex process that involves additions, losses, transformations, and translocations, along with environmental parameters. There are four major soil types in Southern Asia, namely (1) deeply colored and mountainous soils, (2) yellow and red soils, (3) brown soils, and (4) desert soils.
Southern Asia is surrounded by three main water bodies, namely the Arabian Sea, Indian Ocean, and Bay of Bengal. Southern Asia is broadly divided into four climatic zones (1) dry, subtropical, continental climate (northern Pakistani uplands and Indian edge), (2) tropical climate (in areas of Bangladesh, northwest India, and the center of India/Pakistan, (3) equatorial climate (south-west Sri Lanka and far south India), and (4) alpine climate or the Himalayan range. The vegetation in Southern Asia varies depending on the altitude and climate, ranging from

2. Effect of soil deterioration on food production systems
Soil degradation hinders the crop production. There are many types of soil degradation, all of which ultimately affect crop production. In Southern Asia, ~140 Mha of agricultural land is experiencing soil erosion, declining soil fertility, waterlogging and groundwater depletion (Jahan and Gurung, 2017) [16]. The detailed impacts of various soil degradation processes on food crops in Southern Asia are discussed below.

2.1 Soil Erosion
Erosion is the loss of soil through mechanical or physical processes. There are two types of soil erosion: (i) water erosion and (ii) wind erosion.

The land area affected by erosion is estimated to be ~ 83 Mha by water and 59 Mha by the wind in Southern Asia. Soil erosion in the Southern Asia occurs due to both natural and anthropogenic causes like higher rainfall intensity, cultivation on steep slopes, seasonal dry spells in arid regions, naturally erodible and unstable soils, overgrazing, inappropriate use of inorganic fertilizers, deforestation, burning of crop residues, removal of crop residues for animal feed, and continuous monocropping, which are directly or indirectly linked to depleted soil fertility, reduced biodiversity, increased greenhouse gas (GHGs) emissions, denuded topsoil, polluted water quality, low crop yields, and jeopardized human wellbeing (Lal, 2017; Panagos and Katsoyiannis, 2019) [18, 24]. The impact of soil erosion is more severe in hilly areas and in semi-arid regions where both wind and water act as major agents of erosion.

Soil erosion removes not only the macronutrients and topsoil but also the soil micronutrients such as zinc (Zn), iron (Fe), selenium (Se), and boron (B), leading to nutrient deficiencies in food and thus malnutrition, especially in children (Blaylock, 2017) [6]. Erosion also causes siltation of reservoirs, which decreases the capacity of the dams to store water and increases the risks of floods during the rainy seasons. These floods affect the cultivated crops and the quality of the produced grains. In conclusion, accelerated soil erosion is a serious threat to achieving food security in Southern Asia.

2.2 Reduction of Soil Fertility

The surface soil contains soil organic matter (SOM) and plant nutrients. Most agricultural soils in Southern Asia are extremely low in SOM (usually < 1%) and as much as 42.4 Mha of agricultural soils in Southern Asia are severely depleted with SOM. Moreover, excessive use of unbalanced synthetic fertilizers, less use of manures, and removal of crop residues for animal feed and other uses exacerbate the soil erosion hazard, which severely degrade soil fertility (FAO, 2015; Ali *et al*., 2017) [8, 2]. Thus, an effective erosion control, by using no-till (NT) or conservation agriculture (CA) with manuring is essential to obtaining and sustaining higher crop yields (Alam *et al*., 2017) [1].

Most countries of Southern Asia have a negative nutrient budget on croplands. For example, negative balances for different soil nutrients have been reported for 15 agro-ecological regions in India for potassium (K) and phosphorous (P) in Sri Lanka, and for K in Pakistan and all macronutrients in Nepal and Bangladesh (Rehman, 2019) [28]. This negative nutrient budget depicts the ongoing depletion of soil nutrient reserves in Southern Asia countries.

The problem of soil fertility is also execrated by the imbalanced use of synthetic fertilizers. The farmers in most regions are using more N fertilizer relative to K and P. This excessive use of N boosts the crop growth which removes soil-based K and P, thus resulting in their deficiencies in soil. The deficiency of some micronutrients (e.g., sulfur and Zn) has also been reported in India, Pakistan, Bangladesh, and Sri Lanka (Sapkota *et al*., 2016) [29]. Continuous cereal-based rotation with most intensive tillage practices is one of the main causes of rapid soil fertility loss in Southern Asia.

In rainfed regions of Southern Asia, important reasons for low SOM include accelerated erosion which truncates the topsoil layer; excessive and uncontrolled grazing, and removal of crop residues for animal feed and other uses. Further, in situ burning of crop residues is widely practiced in the rice-wheat (cropping system to facilitate the seeding of wheat following rice which also reduces the SOC stock (FAO, 2015) [8].

In dry regions of Southern Asia, where summer temperatures can exceed 45 °C, there is a rapid decomposition of SOM. The introduction of semi-dwarf varieties of rice and wheat in Southern Asia since the 1960s, the emphasis on the use of synthetic fertilizers with lesser use of organic amendments, has also depleted the SOM content. Other reasons for low SOM include the use of monocropping, plough tillage (PT), excessive grazing, deforestation, and continuous cropping without incorporation of a cover crop in the rotation. In addition to depleting SOM, these factors are also the reason for stagnant/declining soil productivity in Southern Asia and jeopardizing the food security of this densely populated region.

2.3 Degradation of Soil Structure

Soil structure refers to the arrangement of the soil particles and the stability of soil aggregates. Wind and water erosion–induced SOM depletion leads to the destruction of soil structure. Rice is a major cereal crop in Southern Asia, and its conventional cultivation requires soil puddling which degrades soil structure, adversely affects the activity of soil biota, increases soil compaction for post rice crops, alters soil hydraulic conductivity, reduces soil water storage, decreases the permeability of air, causes a poor crop stand, and reduces yields of post rice crops (Ali *et al*., 2017) [2].

Some experiments in Southern Asia have shown an increase in subsurface compaction using heavy machinery and puddling (Sidhu *et al*., 2014) [31]. In some areas, water runoff and erosion are common due to soil compaction. Furthermore, the conversion of forest to crops and urbanization is denuding vegetative cover and degrading soil structure in Southern Asia (Hassan *et al*., 2016; Srinivasarao *et al*., 2014) [12, 32].

2.4 Climate Variability

With the current and projected climate change, water shortages and heat stress are major challenges to sustaining agricultural production and advancing food security in Southern Asia (Iizumi and Ramankutty, 2016) [14]. Increased pollution and the growing demand for food and energy in Southern Asia are affecting the availability of freshwater. The productivity of rice is threatened by water scarcity in Southern Asia especially in India. In some Southern Asia countries, water stress caused by low rainfall and less availability of irrigation water has forced farmers to grow alternate crops (author personnel observation) because of low rice yields. In rainfed regions, drought stress reduces crop yields due to erratic rainfalls and non-availability of water harvesting structures (Islam *et al*., 2017) [1].

Most cropping areas in Southern Asia are under the subtropical semi-arid climate, which is among the global hotspots of heat stress. Climate projections for Southern Asia in the twenty-first century indicate considerable warming coupled with the extreme heat wave and precipitation events. Most of the crops in Southern Asia are already being grown at their threshold for heat tolerance (Mbokodo *et al*., 2020) [21]. For the rice-wheat cropping system in Southern Asia, wheat grown after the rice is prone to heat stress during reproductive and grain filling stages which reduces the grain yield. If the present climate change–induced water and heat stress continue until 2050, the yields of maize, wheat, and rice will decrease by 17, 12, and 10%, respectively, in Southern Asia (CGIAR, 2016) [7]. Thus, the challenge for Southern Asia countries is to produce more food using less water under unfavorable climatic conditions to enhance water productivity.

2.5 Soil Salinity and Inundation

Soil salinity is the accumulation of salts in the root zone that hampers plant growth, with adverse impacts on food security and human livelihood. Saline soils occur throughout Southern Asia due to prevailing soil erosion, shallow groundwater tables, tsunamis and inappropriate use of canal water. Salinization and waterlogging occurs on an area of 17 and 12 M ha, respectively, in Southern Asia. The problem of waterlogging is common in the areas receiving heavy monsoon rainfalls and soils of loamy to clayey texture. In the Indo-Gangetic plains, an increase in the underground water table has been noted since the implementation of various irrigation schemes more likely in low-lying areas.

Groundwater is a major source of irrigation water in semi-arid regions of Southern Asia, but the salt levels in groundwater and hydraulic disturbances are aggravating soil salinity. Environmental impacts of groundwater use in Southern Asia include declining water table and quality and increasing soil salinity and the latter is also observed in Sri Lanka on the irrigated areas of the Mahaweli scheme. An increase in the coastal soil salinity is reported in some regions of Bangladesh (Chen and Mueller, 2018). Accumulation of salts on the upper soil surface forms an impervious layer interrupting the infiltration of rainwater causing waterlogging. In conclusion, soil salinity and waterlogging have emerged as serious soil issues in Southern Asia.

2.6 Heavy Metal Poisoning

In Southern Asia, urban agriculture and peri-urban agriculture predominantly depend on sewage water irrigations which are mostly mixed with industrial wastewater and contaminate the soils and crops with heavy metals which include arsenic, cadmium, chromium, copper, and manganese (Proshad *et al*., 2019) [25]. Arsenic contamination, especially in underground water, is a big threat to the human population who depends on underground water for drinking. Moreover, this arsenic may accumulate in plant parts through the soil and may cause serious health issues after entering the human food chain (Azam *et al*., 2017) [3]. In Southern Asia, Pakistan, India, and Bangladesh are mostly affected countries by heavy metal toxicity (Shahid *et al*. 2020) [30]. Contamination of rice with arsenic has also been reported in the literature (Proshad *et al*., 2019) [25] which is a big threat to the people who consume rice as a staple food. Most of the reported data is survey based or presents specific locations, but in-depth studies presenting the complete data on soil and water contamination with heavy metals in Southern Asia countries are still unclear and need further investigations.

2.7 Loss of Biological Resources

Biodiversity implies the diversity within different life forms (below and above ground) of an ecosystem. Soil biodiversity improves water entry and storage in soil, plant nutrition, and resistance to soil erosion, controls pests and diseases, and facilitates SOM recycling (Wachira *et al*., 2014) [34]. Loss of biodiversity disrupts the functioning of the food web, nutrient recycling, N fixation, carbon sequestration, organic waste recycling, and soil resilience. The latter is affected by adverse changes in soil structure, water holding capacity (WHC), and infiltration, bioremediation capacity, genetic resources, above-ground biodiversity, and incidence of plant pests and diseases.

Accelerated soil erosion, along with crop intensification, not only affects soil fertility but also the below and above ground biodiversity, including crop genetic diversity and wild diversity which finally reduces the SOM content. Land use changes cause significant alterations in soil fauna and flora (Rahman *et al*., 2012) [26] which are affecting long-term biodiversity in Southern Asia.

3. Sustainable Land Management Practices

3.1 Restitution and Handling of SOM

Sustainable management of SOM is essential to successful crop production in Southern Asia. However, different strategies are needed for different soil types and climatic conditions. Each approach is based on the principle of increasing biomass production and its return to the soil, thereby improving the amount of active SOM, which improves soil porosity, nutrients, and water holding capacity.

The SOM levels can be restored with the adoption of recommended soil management practices. For example, cover crops promote the supply and accumulation of SOM and improve soil quality, minimize risks of soil erosion and nutrient leaching, and enhance atmospheric N fixation (Wittwer *et al*., 2017) [35]. Growing of summer legumes [e.g., *Sesbania* spp., mungbean (*Vigna radiata* (L.) Wilczek), and cowpea (*Vigna unguiculata* (L.) Walp.)] as green manure between wheat harvest and rice transplanting can improve soil fertility in rice-wheat cropping system.

Balanced fertilization may improve SOM by increasing plant biomass and enabling good amounts of residues to be returned into the soil, while competing uses of crop residues are an important determinant in obtaining higher SOM contents by improving fertilizer use efficiency for better growth, yields, and biomass production. In general, high biomass production increases the population and activities of soil microorganisms. Conversely, soils with lower SOM have lower fertilizer use efficiency and low productivity. Site-specific adoption of cover crops and agro forestry has multiple benefits for providing fiber, fuel wood, and biocontrol (e.g., neem) and improving soil fertility, SOM, and soil fauna (Heckman, 2015) [13].

Crop residue management in agro-ecosystems adds SOM that improves soil quality, water infiltration, and nutrient availability. It also buffers soil pH, sequesters carbon, controls erosion, improves soil biological activity, reduces evaporation, and prevents soil surface from desiccation (Ghimire *et al*., 2017) [9].

Excessive ploughing disrupts soil aggregates, degrades structure, reduces water holding capacity, exposes the protected SOM to microbial processes causing its faster degradation, and promotes emission of GHGs from the rice field. Plough tillage increases heterotrophic microbiological activity in soil and increases mineralization rate with the subsequent decline in soil structure. However, reduced or zero tillage maintains heterotrophic microbial activity. In general, reduced tillage systems may increase SOM under diverse soil types (Ghimire *et al*., 2017) [9], when practiced over a long time.

3.2 Efficient Utilization of Water and Runoff Management

Numerous techniques can be used to harvest rainwater for the management and utilization of runoff. The harvested water can also be used for livestock and domestic purposes (Recha *et al*., 2015) [27].

There are many examples of successful rainwater harvesting systems in Southern Asia. For example, micro-catchment rainwater harvesting systems (*viz.*, contouring, terracing, pitting, and micro basins) are designed to collect runoff from small catchment areas (*i.e.*, 10–500 m^2). Techniques of in situ rainwater harvesting include ridging, mulching, furrowing, and conservation tillage (Biazin *et al*., 2012) [5].

Flood irrigation, the most common method of irrigation in Southern Asia, causes nutrient leaching and excessive use of water. Thus, alternate water-saving irrigation (e.g., sprinklers and drip) and sowing/planting methods (e.g., bed, and ridge sowing), irrigation based on matric potential, direct-seeded aerobic rice systems, construction of underground pipelines, sowing of short duration cultivars, and adjustment of paddy transplantation date with rain forecast may improve the water use efficiency (WUE) in Southern Asia.

3.3 Nutrient Management Practices for Sustainable Crop Productivity and Soil Fertility Maintenance

Data from several long-term experiments on diverse soil types and climatic conditions indicate that the synthetic fertilizers alone are not sufficient to increase or sustain soil fertility, and may aggravate soil acidification (Basso *et al*., 2016) [4]. On the other hand, the sole use of organic fertilizers can improve soil fertility and quality, but the crop responses to sole organic amendments are slow. Moreover, the farmer in the region did not apply micronutrient to soil. Thus, application of micronutrients (e.g., Zn) and bio-inoculants, and the combined use of organic and inorganic (synthetic) fertilizers (micro and macro)/amendments (Srinivasarao *et al*., 2019) [33], might be attractive options to improve soil health and crop productivity on a sustainable basis

Further, the combined application of inorganic synthetic fertilizers and organic manures [*i.e*., farmyard manure (FYM)] improved soil microbial properties; reduced nutrient losses; increased SOC, aggregation, and WHC; reduced bulk density, enhanced total N, SOC, microbial biomass N/carbon, and the activities of different soil enzymes (dehydrogenase, urease, and alkaline phosphatase) and produced higher crop yields. Several studies have reported higher crop yields with combined application of organic and inorganic fertilizers than their sole application with substantial improvements in earthworm activity and reductions in acidification (Basso *et al*., 2016) [4].

The temporal crop diversification with planned crop rotations is useful to increase soil fertility than monocropping. For example, the losses of N and carbon are less with legume based crop rotations. Likewise, N application should be made on the basis of the crop growth stage, soil N status, and crop N demand. In-season, site-specific strategy for N management can improve the efficiency of N uptake compared with that under farmer practice (Miao *et al*., 2011) [22]. Thus, combining the precision nutrient management principles and practices with modern crop management technologies is important to developing sustainable nutrient management systems in Southern Asia. The foliar sprays are a short term strategy for improving micronutrient status in Southern Asia. Whereas, long-term strategies for micronutrient management may include breeding crop varieties that are better able to harvest micronutrients from the soil. Crop fertilization based on Leaf Color Chart (LCC) using SPAD chlorophyll meter or based on soil test might also be useful for sustainable nutrient management in Southern Asia.

For the control of water erosion, it is recommended to construct small check dams, adopt prudent and efficient management of the watershed, undertake afforestation on steep slopes upstream, and use river current for electricity generation. First order gullies are the principal conduits to feed into the second and third order gullies.

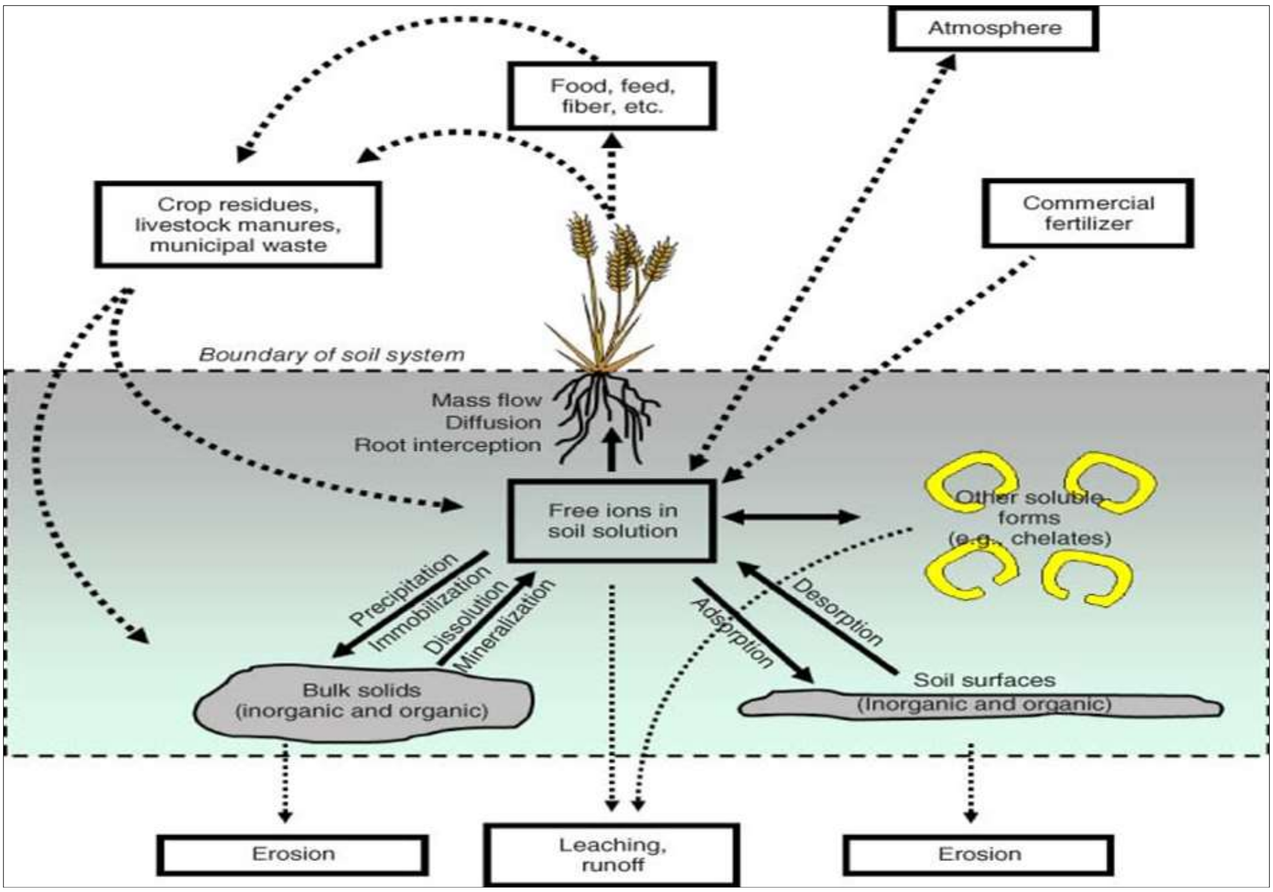

Fig 1: Overview of nutrient behavior. Dashed lines represent nutrient gains or losses in the soil system; solid lines represent internal transformations within the soil system. Sustainable crop production requires that nutrient losses and exports in crop products are balanced by nutrient imports and recycling (Grant, 2017) [10]

3.4 Efficient Utilization of Resources in Conservation Agriculture

Conservation agriculture (CA) is a pragmatic tool for soil management in Southern Asia for optimum productivity. Conservation agriculture encompasses minimal soil disturbance, permanent soil cover, diversified crop rotations, and integrated weed management. The introduction of conservation agriculture has helped farmers worldwide to improve crop yields with substantial reductions in soil degradation and production costs. It also improves soil physical (less soil compaction, higher soil moisture, and SOM) and biological properties (increased microbial activity, soil enzyme activity, soil biomass carbon/N) (Jat *et al*., 2011) [17]. The potential of conservation agriculture is not realized in Southern Asia despite the implementation of a number of government-sponsored schemes because conservation agriculture needs to transition period of 3–5 years to get potential soil and yield benefits. Advancing food security through conservation agriculture in Southern Asia requires more attention and investment in agricultural development with a focus on poverty reduction, mitigation of GHGs emissions, and improvements in soil properties. The farmers should be compensated during the initial years of conservation agriculture, which will also contribute to reducing rural poverty.

Crop diversification in the conservation agriculture systems may also improve productivity and profitability in Southern Asia. Crop diversification is an eco-friendly, cost-effective, and most rational way to reduce uncertainties within agriculture, especially for farmers with small landholdings in Southern Asia. In general, crop diversification increases the temporal and spatial biodiversity on farmland enhances soil fertility, and stabilizes yields. The diversified cropping systems are agronomically more resilient and stable as they reduce pest and disease pressure and decrease the N fertilizer use and soil erosion (Lin, 2011) [19].

Several resource conserving technologies (e.g., permanent beds, tensiometer-based irrigation, direct-seeded rice, and zero tillage, laser land leveling) are recommended based on site-specific soil and climate which can reverse the declined soil structure and may improve water productivity in Southern Asia.

3.5 Carbon Capture and Storage

Restoring soil carbon stocks is a promising, cost-effective, and a natural process of limiting global warming with numerous co-benefits. The establishment and management of forests, croplands, and rangelands have the potential to sequester large amounts of SOC for increasing soil fertility, reducing soil erosion, retaining soil moisture, mitigating climate change, and promoting soil biodiversity. SOC releases nutrients for plant growth that promote soil health and acts as a buffer. It is concentrated in the topsoil, which contains 0.5–3% SOC for most natural, upland soils. Management practices that enhance SOC include conservation agriculture, improved crop management, agroforestry systems, improved management of grazing lands, and the addition of organic materials such as manure and compost (Craggs, 2016).

Another increasingly used management strategy for improving SOC is the growing of cover crops [e.g., alfalfa (*Medicago sativa* L.), clover (*Trifolium* species), and other legumes], which provide soil cover and thus hold water, maintain soil structure, facilitate drainage, and add SOM. The use of biochar may be another option to increase the SOC contents in Southern Asia. In a recent study from India, biochar application along with inorganic fertilizers in wheat-green gram [*Vigna radiata* (L.) Wilczek] crop rotation documented more effective in sequestering carbon compared with vermicompost.

Implementation of the 4 per Thousand Initiative (launched at the 21st meeting of the Conference of the Parties (COP21) in Paris) is committed to helping farmers in developing countries to implement specific farming practices. The practices include the adoption of a system-based conservation agriculture and use of organic manure rather than synthetic fertilizers. This will help to sequester carbon to repair, nurture, and sustain soils and have the potential to contribute significantly higher SOC levels thus improving the soil health (Craggs, 2016). In Southern Asia, the promotion of conservation agriculture in the rice-wheat cropping system has improved carbon sequestration.

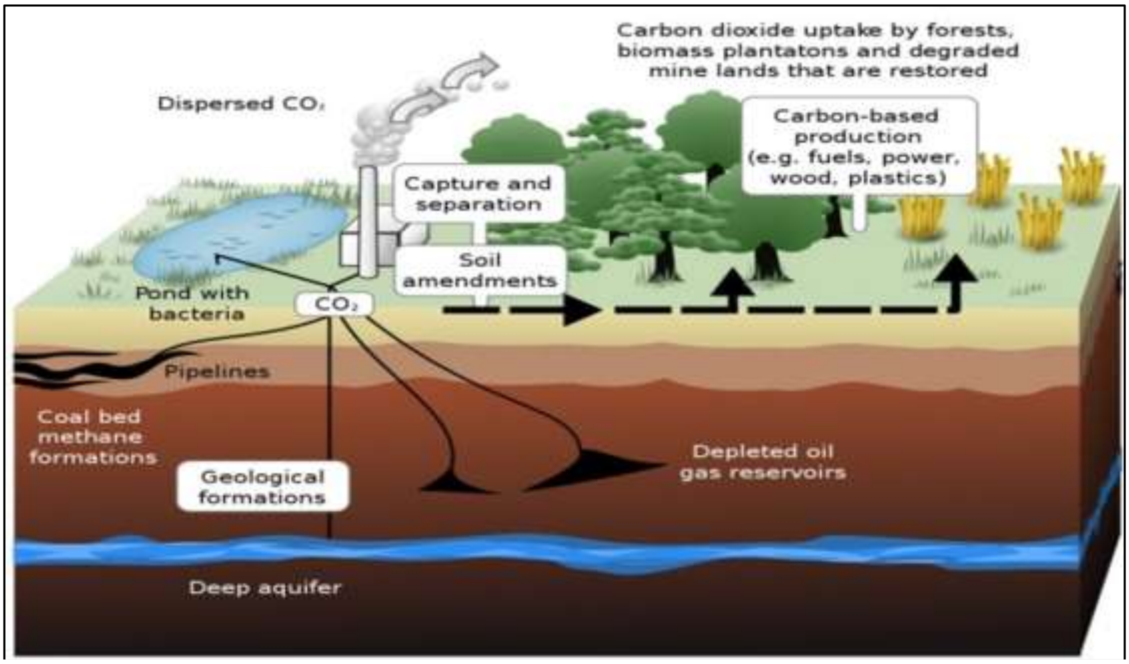

Fig 2: (Lovelace and Temple, 2012) [20]

3.6 Handling of Heavy Metal Poisoning

Different management techniques have been proposed by the researchers to manage crop production in heavy metal–contaminated soils. Amendments of soils with biochar have been shown to have a positive impact to reduce the soil cadmium toxicity. The positive effect of biochar in the alleviation of cadmium toxicity in wheat, rice (Hafeez *et al*., 2019) [11] and muskmelon (*Cucumis melo* L.) have been reported (Zou *et al*. 2020) [36]. Use of plant growth promoting rhizobacteria and mycorrhizal fungi and growing of special crops for phytoremediation of heavy metals are alternative option to reduce the risk of heavy metal toxicity effects on crop growth. To avoid the direct threat of heavy metals to human health, such crops should be used which store heavy metals in non-food parts or crops should be used which are not consumed for food (Mishra *et al*., 2017) [23].

4. Conclusions

1. The ever-increasing population in Southern Asia has highlighted the need to produce more without further expansion of the cultivated land area. Population control is a high priority.
2. The use of productive agricultural land for urbanization and brick making, and excessive tillage practices has threatened the long-term food security in Southern Asia. Removal of soil from the agricultural lands for brick making should be discouraged; rather the soil should be mined from the wasteland.
3. Monocropping for extended periods has caused biodiversity loss and created pest and disease problems. Crop diversification by including legume crops in cereal-based cropping systems is useful in improving soil fertility and increasing biodiversity.
4. Fertilization must be done based on soil test, Leaf Colour Chart, or leaf SPAD. Using farmyard manure, compost, green manures, biochar, and cover crops is a pragmatic strategy for restoring soil organic matter content.
5. Micro and macro rainwater harvesting systems in rainfed areas of Southern Asia might serve as a water source for crops in the dry season, which can also be used for fish rearing, aquifer recharge, and other domestic purposes. Small dams should be installed in rainfed areas to decrease soil erosion and store rainwater for crop production and other domestic uses.
6. Adoption of system-based conservation agriculture offers a pragmatic option for sequestering soil carbon, reducing soil erosion, and improving soil organic matter content.
7. Payments to farmers for ecosystem services may be useful for promoting the adoption of conservation agriculture, which can restore soil health and advance food security in Southern Asia.

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