

Saving global land resources by enhancing eco-efficiency of agroecosystems

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Expansion of land area under agroecosystems has numerous ecological and environmental consequences. Important among these are decline in habitat of natural species and reduction in biodiversity, increase in risks of accelerated erosion and nonpoint source pollution, and emission of greenhouse gases (GHGs; carbon dioxide [CO₂], methane [CH₄], and nitrous oxide [N₂O]) from the terrestrial biosphere into the atmosphere with the attendant increase in the risks of global warming. Thus, a great challenge facing humanity lies in advancing the Sustainable Development Goals of the United Nations (United Nations 2014) while restoring quality of natural resources (soil, water, and air) and saving land for nature conservancy. Therefore, the objective of this article is to discuss the conceptual basis of land-saving technologies for advancing food and nutritional security while improving the environment, adapting to and mitigating anthropogenic climate change, and enhancing biodiversity. This paper specifically focuses on one important dimension of the food security debate, and that is on the need to reduce (rather than expand) the use of land area, water, fertilizers, and pesticides, while achieving food and nutritional security and restoring the environment. The discussion provides hypothetical scenarios for increasing agricultural production while reducing the land area under agriculture along with reduction in the amount of water consumed for irrigation and a decline in the use of fertilizers.

GLOBAL LAND AREA FOR AGRICULTURE

Of the earth's total land area of 1.49×10^{10} ha (3.68×10^{10} ac), 1.04×10^{10} ha (2.57×10^{10} ac) is the habitable land. Of the habitable land, 5.1×10^9 ha (1.26×10^{10} ac) is under agriculture (1.17×10^9

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Table 1

Estimates of present (2000) and future (2030) land use (adapted from Lambin and Meyfroidt [2011], Gibbs and Salmon [2015], Bai et al. [2008]).

Land use	Land area (ha $\times 10^6$)	
	In 2000	Additional land area by 2030
Cropland	1,510 to 1,611	81 to 147
Biofuel crops	—	44 to 118
Grazing land/ pastures	2,500 to 3,410	0 to 151
Natural forests	3,143 to 3,871	—
Planted forests	126 to 215	56 to 109
Urban land	66 to 351	48 to 100
Unused productive land	356 to 445	—
Land lost to soil degradation	500 to 1,000	30 to 87

Note: Estimates of vegetation degradation may be on 24% of the earth's land area (Bai et al. 2008).

ha [2.89×10^9 ac] for crops and 3.93×10^9 ha [9.71×10^9 ac] for livestock), 3.9×10^9 ha (9.64×10^9 ac) is under forests, 1.2×10^9 ha (2.97×10^9 ac) under shrubs and prairies, 1.5×10^8 ha (3.7×10^8 ac) under urban land, and 1.5×10^8 ha (3.7×10^8 ac) under fresh water reservoirs (Roser and Ritchie 2017). The data on present and future land use shown in table 1 are based on the assumption that additional area would be needed for cropland, biofuel feedstocks, grazing land, and urbanization. In addition, as much as 3×10^7 to 8.7×10^7 ha (7.4×10^7 to 2.1×10^8 ac) would be lost to degradation processes such as erosion, salinization etc. (table 1). Estimates of additional resources needed by 2050 and beyond have been widely reported (Alexandrotos and Bruinsma 2012; Asubel et al. 2013; Bruinsma 2009; FAO 2009).

Conversion of natural land to agricultural ecosystems has been a prominent source of GHGs ever since the dawn of settled agriculture (Ruddiman 2003), and it has strongly affected the terrestrial carbon (C) balance. Gaseous emissions due to anthropogenic land cover change were large during the pre-industrial era (Reick et al. 2010). Estimates of the historic depletion of soil organic C (SOC) stock range from 135 Pg C (1.49×10^{11} tn C) (Lal 2018) to 133 Pg C (1.47×10^{11} tn C) (Sanderman et al. 2017). It is also argued that historic CO₂ emissions from

land use change may have been underestimated (Arneeth et al. 2017), and that the early per capita land use change was larger than reported (Ruddiman and Ellis 2009). Land cover change has also caused a strong decline in terrestrial biodiversity (Newbold et al. 2015). Therefore, any additional conversion of land from natural to agricultural and other managed (urban) ecosystems requires a critical and an objective consideration.

ANTHROPOGENIC IMPACTS ON SOIL AND OTHER NATURAL RESOURCES

Intense anthropogenic activities, especially since the 1960s, have strongly impacted the biogeochemical and biogeophysical cycles of water, C, nitrogen (N), and other elements. As much as 38% of the earth's terrestrial surface is already used for agriculture, of which three-fourths is used for raising livestock. About 70% of the global fresh water withdrawal is used for irrigation, and 30% to 35% of GHG emissions are contributed by agriculture. Yet, 1 in 9 persons (795 million people) are food-insecure, and 2 to 3 in 7 are malnourished and prone to hidden hunger (FAO 2015). Thus, there is a strong need of a paradigm shift in business-as-usual of managing agroecosystems.

There have also been drastic changes in the global N cycle, especially since the Industrial Revolution circa 1750. The global N fixation of 203 Tg (2.2×10^8 tn

in the preindustrial era has increased to 418 Tg (4.6×10^8 tn), including 140 Tg N y^{-1} (1.5×10^8 tn N yr^{-1}) by biological N fixation in marine ecosystems (Canfield et al. 2010), 5 Tg N y^{-1} (5.5×10^6 tn N yr^{-1}) by lightning (Tie et al. 2002), and 58 Tg N y^{-1} (6.4×10^7 tn N yr^{-1}) in terrestrial ecosystems (Vitousek et al. 2013; Fowler et al. 2013; Herridge et al. 2008; Battye et al. 2017). In addition, the reactive N produced by the fertilizer industry is 125 Tg N y^{-1} (1.4×10^8 tn N yr^{-1}). Of the 418 Tg of reactive N, 215 Tg (2.4×10^8 tn; 51.4%) of the anthropogenic origin (Lal 2017a) is a cause of environmental pollution, including eutrophication, acidification of water, and emission of N_2O into the atmosphere. Indiscriminate use of nitrogenous fertilizers has been responsible for these environmental concerns. Addition of phosphorus (P) as a fertilizer is another source of pollution, especially of algal bloom. A total cereal grain production of 2.508×10^9 t (2.765×10^9 tn) in 2014 (FAOSTAT 2017) is achieved because of fertilizer use. However, the amount of N and P fertilizers applied in 2014 (1.133×10^8 t [1.249×10^8 tn] of N and 2.05×10^7 t [2.26×10^7 tn] of P) were about 2.5 times more than that harvested in the grains. A large proportion of excessive fertilizer used is leaked into the environment and leads to emission of N_2O and eutrophication of water as indicated by the growing problems of algal bloom and the hypoxia of coastal waters.

CLIMATE CHANGE EFFECT ON SOIL RESOURCES AND CROP YIELD

Increase in temperature related to projected global warming could lead to a net loss of global soil C stocks during the twenty-first century with a strong positive feedback such as the so-called, “compost-bomb instability in drying organic soils” (Luke and Cox 2011). It is estimated that global SOC stocks may decrease by 30 ± 30 to 203 ± 161 Pg C ($3.31 \times 10^{10} \pm 3.31 \times 10^{10}$ to $2.24 \times 10^{11} \pm 1.78 \times 10^{11}$ tn) for each $1^\circ C$ ($1.8^\circ F$) increase in temperature, and that the loss of SOC from the upper soil horizons by 2050 may be as much as 55 ± 50 Pg ($6.06 \times 10^{10} \pm 5.51 \times 10^{10}$ tn) (Crowther et al. 2016).

South America, a region where agricultural expansion is occurring and presumably

can occur, has its own environmental issues. The adverse impacts of the half a century of the process of economic integration of the Amazon on soil, water, biodiversity, and other natural resources cannot be overemphasized. The Amazon region, similar to that of Sumatra and the Congo Basin, may have two tipping points: (1) temperature increase of $4^\circ C$ ($7.2^\circ F$) by the projected climate change, and (2) deforestation exceeding 40% of the forest cover (Nobre et al. 2016). Thus, there is a strong need for a new global agricultural paradigm.

ENHANCING ECO-EFFICIENCY

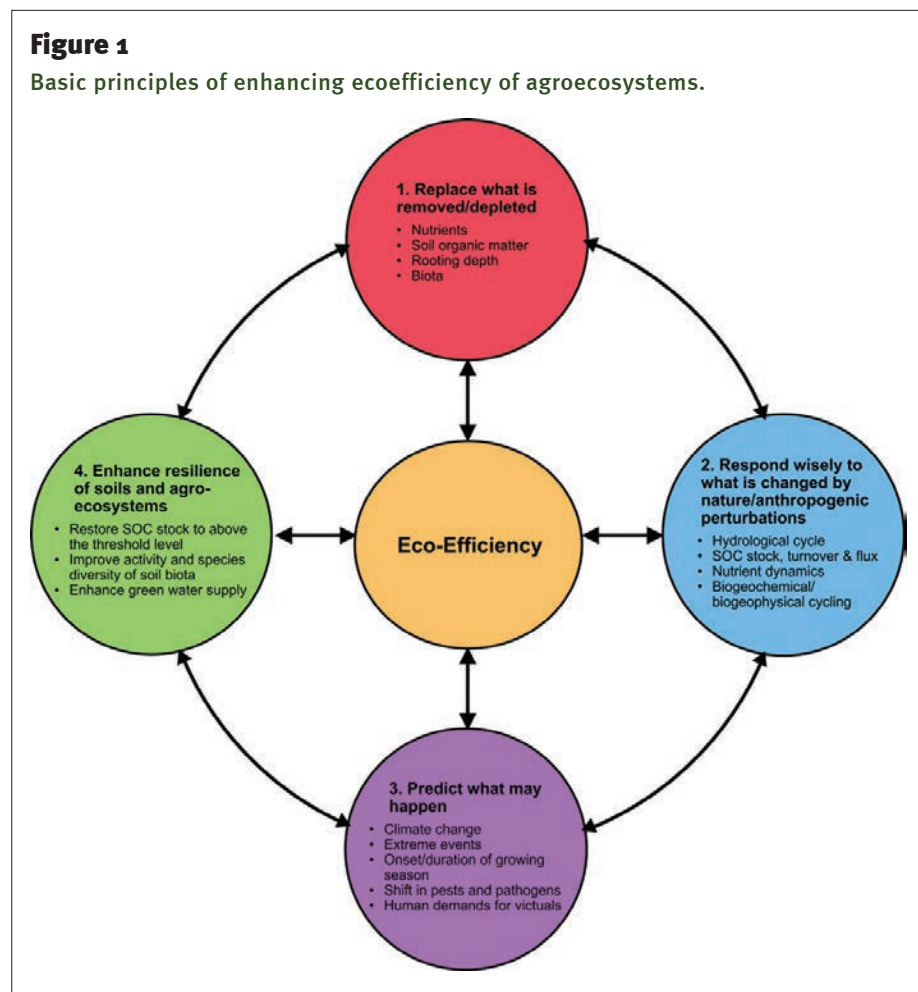
The basic strategy is to enhance the use efficiency of inherent (i.e., plant nutrients and water) resources and external inputs (i.e., fertilizer, water, energy, and pesticides) by reducing losses (i.e., erosion, leaching, and volatilization). The goal is to increase agronomic productivity per unit of land area and per unit input of nutri-

ents, pesticides, agrochemicals, energy, and emission of GHG. It is critical to adopt site/soil-specific best management practices (BMPs), narrow the yield gap (the difference between the attainable yield and the national average yield), and sustain productivity growth. Implementation of this strategy involves (1) replacing what is removed or depleted, (2) responding wisely to what is changed, (3) predicting what may happen to soil and water resources in the future, and (4) enhancing resilience of soils and agroecosystems (figure 1). Rather than expanding the land area under agricultural production, conversion of traditional to improved systems can save land for nature conservancy and restoration. The objective is to produce more from less and save resources for nature restoration and conservation.

There are several land saving options. For example, Phalan et al. (2016) proposed the following four linking mechanisms:

Figure 1

Basic principles of enhancing ecoefficiency of agroecosystems.



1. Land use zoning or “using the best and saving the rest” following the Boserpian innovation concept (an increase in population would stimulate technologies to increase food production, and the necessity is the mother of invention). Some ecologically sensitive ecoregions can be protected (off-limits), such as the tropical rainforest or highly erodible lands.
2. Incentivizing the adoption of BMPs through payments for ecosystem services, such as the Conservation Reserve Program in the United States,
3. Promoting knowledge-based soil- and site-specific BMPs for enhancing yield (e.g., conservation agriculture, cover cropping, improved varieties and species, and drip subirrigation). Supplemented irrigation can lead to multiple cropping.
4. Adopting labor and capital-intensive technologies. This strategy is rooted in balancing economic and ecological goods by recognizing the ecological value of ecosystems (Frank and Schlenker 2016).

In this regard, agricultural innovation is essential to restoring and protecting the environment for a world of 11.2 billion people.

ENHANCING SOIL ORGANIC CARBON AND RESTORING SOIL HEALTH

Enhancing SOC concentration and stock in the root zone to above the critical level (1.5% to 2.0% SOC or 3% to 4% soil organic matter content) is essential

to enhancing soil health (Lal 2016b). Soil health refers to the capacity of soil to function as a vital living system to sustain biological productivity; maintain environmental quality; and promote plant, animal and human health (Doran et al. 2002). Soils of agroecosystems must be restored through a soil-centric paradigm shift and by not taking soils for granted. Concentration of SOC in the root zone is the most reliable indicator of the extent and severity of degradation/erosion (Rajan et al. 2010), just as soil health is an indicator of sustainable management (Doran et al. 2002), and of human and animal health (Oliver 1997). A healthy soil can also suppress pathogens and diseases (Larkin and VanAlfen 2015; Janvier et al. 2007) and reduce the dependence on pesticides. Soil health is an integrative property, an indicator of soil’s capacity to respond to innovations (e.g., improved varieties, irrigation, fertilizers, etc.), and a criterion in its ability to deliver essential ecosystem services for human wellbeing and nature conservancy.

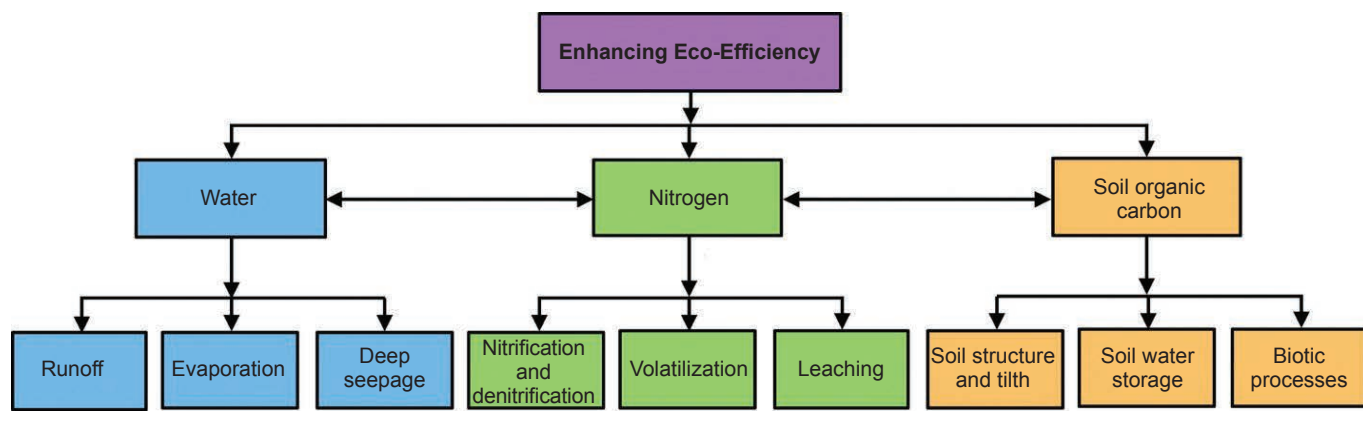
Soil health can be assessed and managed by quantifying the flow of energy and C between functions, which is an essential but challenging task (Kibblewhite et al. 2008). Thus, an integrative soil health test is used to evaluate the impact of soil management (Idowu et al. 2017). Flow of energy and C among functions is intricately interconnected with SOC and its turnover (Lal 2016b).

Adoption of site-specific BMPs is essential to improving SOC and restoring soil health. While there is no one-size-fits-all technology that can be used on 300,000 known soil services worldwide, the basic principle of enhancing SOC concentration is to create a positive soil C budget—input of biomass C into the soil must exceed the losses of C by erosion, mineralization, and leaching. A system-based conservation agriculture (i.e., with four components: mulch and residue retention, cover cropping and complex rotations, integrated nutrient management, and no-till) can minimize erosion and enhance SOC concentration and stock (Lal 2015; Amado et al. 1998; Ashworth et al. 2014). The mean residence time of SOC sequestered can be prolonged in soils (deep solum, high clay + fine silt content, 2:1 type expanding clays with high water holding capacity), which enhance formation of organo-mineral complexes (Newcomb et al. 2017). The strategy is to judiciously manage the coupled cycles of water, SOC, and N by reducing losses of water, managing emission of GHGs, and restoring soil structure and biotic processes (figure 2).

SPATIAL CONTRACTION OF AGROECOSYSTEMS

In Sub-Sahara African (SSA) soils, which bypassed the Green Revolution of 1960s, there is a justifiable need of expanding the land area equipped for irrigation and also increasing the rate of fertilizer input on cropland. On global basis, however, there is an excessive use and gross misuse of

Figure 2
Managing coupled cycling of water, soil organic carbon, and nitrogen.



agricultural land area, irrigation water, fertilizers, pesticides, and other energy-based inputs. Expanding land area and using more inputs is a misguided, no-brainer option and an easy temptation that must be resisted. Indeed, there are better and more environmentally friendly options of advancing the Sustainable Development Goals or the Agenda 2030 of the United Nations.

The world produces enough food already to feed a population of 10 billion. However, food and nutritional security must be achieved by (1) reducing the food waste estimated at 30% to 40% of grains produced globally; (2) increasing access to food by addressing poverty, inequality, political instability, and civil unrest; (3) improving distribution; (4) increasing use of pulses and plant-based diet (Lal 2017b); and (5) increasing agronomic productivity from existing lands by narrowing the yield gap through restoration of degraded soils and recarbonization of soil and the biosphere.

Narrowing the yield gap—especially in developing countries of SSA and South Asia (SA) along with those in Central America and the Caribbean—necessitates restoring degraded soils; enhancing biological N fixation by legumes and nonlegumes (Ferreri et al. 2018); adapting site-specific BMPs for water conservation in the root zone; delivering water and nutrients directly to plant roots at the critical growth stages; and growing improved cultivars and species. Among desirable attributes of production systems that will lead to spatial contraction of agricultural land area are productivity, stability, equitability, autonomy or self-sufficiency, sustainability, and the eco-efficiency. The term “eco-efficiency” implies producing more from less, and the term “sustainability” must be multidimensional: environmental, economic, social, and institutional.

Similar to croplands, even modest improvements in livestock systems can significantly reduce further land expansion for feed production, especially by adapting integrated systems, which improve the efficiency of the entire food system. The presently used land area of 2.506×10^9 ha (6.192×10^9 ac) for raising livestock can be reduced to 2×10^9 ha (4.942×10^9 ac) by improving efficiency. The land area used for cereal production to feed live-

stock (2.10×10^8 ha [5.19×10^8 ac]) can also be saved by grass-fed systems. Animals can be raised on lands not used for crop production and by conversion of coproducts into protein-rich food (Herrero et al. 2013; Mottet et al. 2017). Nutrient management, especially N and P, is the key issue. For example, N, P, and K harvested in corn (*Zea mays* L.) is 36, 8, and 9 kg Mg⁻¹ (72, 16, and 18 lb tn⁻¹) for grains compared with 15, 2, and 37 kg Mg⁻¹ for stover (Bundy 1998). Therefore, stover/straw must be recycled and part of the N demand met through biological N fixation by legume-based rotations (Lal 2017b). Indeed, the current (circa 2000) levels of cereal production can be achieved with 50% less N application, and production with the current level of input could be increased 60% by an efficient spatial pattern of N use (i.e., more in SSA and less in China) (Mueller et al. 2014). The key strategy is of achieving synchrony between N supply and crop demand without excess deficiency (Cassman et al. 2002).

The area equipped for irrigation can be expanded from 3.25×10^8 ha (8.03×10^8 ac) at present to 4.25×10^8 ha (1.05×10^9 ac) by replacing traditional methods (flood, furrow, and sprinkle) by drip subirrigation/fertilization and even vapor condensation systems. By so doing, the water use for agriculture and risks for its eutrophication can be substantially reduced. The land area under permanent pasture can be reduced from 2.5×10^9 ha (6.2×10^9 ac) at present to 1.82×10^9 ha (4.50×10^9 ac) by 2100 (table 2). Thus, the forage demand of 6×10^9 Mg y⁻¹ (6.6×10^9 tn yr⁻¹) at present to 9×10^9 Mg y⁻¹ (9.9×10^9 tn yr⁻¹) in 2100 can be met by enhancing average forage production from 2,400 kg ha⁻¹ (2,141 lb ac⁻¹) at present to 4,950 kg ha⁻¹ (4,416 lb ac⁻¹) in 2100 by improved species and better management. However, improving forage production is more challenging a task than is increasing grain production because of drier environments and marginal lands.

Table 2

Hypothetical scenarios of the land area, irrigation water, and global fertilizer use for production during the twenty-first century (Adapted from Lal 2016a, 2017a; Mottet et al. 2017). Numbers in parentheses reflect the present situation.

Land area	Year			
	2005 to 2007	2050	2080	2100
Cereal production				
Production (10 ⁶ Mg)	2,012	3,012	3,350	3,540
The desired yield (kg ha ⁻¹)	3,280	5,000	6,000	7,000
Required land area (Mha)	613	600	560	500
Pulses and food legumes				
Production (10 ⁶ Mg)	(70)	443	485	511
The desired yield (kg ha ⁻¹)	(700)	1,800	2,010	2,150
Required land area (Mha)	(85.6)	245	240	238
Livestock				
Forage production (10 ⁹ Mg)	(6)	7.2	8.1	9.0
The desired forage yield (kg ha ⁻¹)	2,400	3,230	4,130	4,950
Required land area (Mha)	(2,506)*	2,230	1,985	1,820†
Global fertilizer need (10 ⁶ Mg)	(200)‡	160	120	100
Irrigated land area				
Conversion to DSI and fertigation (Mha)	(325)	365	400	425
Volume of water use (km ³ y ⁻¹)	(3,986)	3,200	2,480	2,000

*The reported area of permanent grassland in 3,500 Mha (FAOSTAT 2017) of which 1,500 Mha is marginal lands.

†Mottet et al. (2017) estimated that 685 Mha of grassland currently used will be converted to other uses.

‡Present fertilizer use is 200×10^6 Mg y⁻¹ (FAOSTAT 2017) and it can be reduced by 50% and redistributed spatially.

There is a need to reduce fertilizer use by improving the use efficiency, reducing losses by erosion along with leaching and volatilization, and improving the spatial distribution. The objective is to reduce fertilizer use from 200×10^6 Mg y^{-1} (220×10^6 tn yr^{-1}) at present to 100×10^6 Mg y^{-1} (110×10^6 tn yr^{-1}) by 2100 (table 2) but improve the spatial distribution and reduce losses. In 2016, the rate of fertilizer use (kg ha^{-1} of arable land) was 138 (123 lb ac^{-1}) for the world, 565 (504 lb ac^{-1}) for China, 218 (194 lb ac^{-1}) for Germany, 175 (156 lb ac^{-1}) for Brazil, 165 (147 lb ac^{-1}) for India, 158 (141 lb ac^{-1}) for South America, and only 16 (14 lb ac^{-1}) for SSA. If the average rate of fertilizer for arable land can be increased to 150 kg ha^{-1} (134 lb ac^{-1}) by 2100, the total fertilizer demand for 5×10^8 ha (12×10^8 ac) of land area under cereals will be only 75×10^6 Mg (8.27×10^7 tn). Thus, 100×10^6 Mg y^{-1} (110×10^6 tn yr^{-1}) of fertilizer use for all land uses (table 2) is a feasible estimate. Similar to contracting the land area and the input of chemicals and water, enhancement of eco-efficiency by adoption of proven and known site-specific technologies can save land and water, improve the environment, and meet the needs of the growing and progressively affluent population of India (table 3).

There is a strong coupling of the biogeochemical and biogeophysical cycles of water, C, N, P, and sulfur (S) (Lal 2010). Thus, eco-efficiency can be greatly enhanced by judicious management of SOC and soil water. An optimal range of SOC in the root zone is $\sim 2\%$ (Loveland and Webb 2003). Restoring SOC, to recarbonize the historic depletion of ~ 130 Pg (1.43×10^{11} tn) C from world soils (Lal 2018), has numerous cobenefits. In addition to creating a draw-down of atmospheric CO_2 by ~ 60 ppm, it would enhance soil health, plant available water resources, and the use efficiency of fertilizers and other energy-based inputs. Conventional tillage, including plowing and disking, decreases the abundance and the biomass of earthworms (Jesus et al. 2017), but nature's plow must be fed by retention of crop residues. Soil biota is the bioengine of the earth, and it must be enhanced by regular and appropriate input of biomass, the food source and habitat of soil biota. A

Table 3

A scenario of future land area and inputs for agriculture using soil-centric technology in India.

Parameter	2017	2030	2050	2100
Population (10^6)	1,339	1,513	1,659	1,517
Per capita arable land (ha)	0.12	0.08	0.07	0.065
Cropland area (Mha)	130	120	115	100
Grain production	273	320	370	400
Soil degradation (Mha)	130	100	50	20
Irrigated land area (Mha [km^3])	70 (200)	75 (150)	82 (100)	100 (75)
Fertilizer use (10^6 Mg)	30	25	20	15
In-field residue burning (10^6 Mg)	100	0	0	0
Pesticide use (10^3 Mg)	56	30	20	10
Cereal Yield (Mg ha^{-1})	2.1	2.7	2.8	4.0
Post-harvest losses (%)	34	10	5	5
Organic manure (10^6 Mg y^{-1})	200	300	400	500

widespread adoption of innovative technologies for ensuring environmental services will necessitate explicit policy interventions (Rudel et al. 2009).

CONCLUSIONS

The Green Revolution of the 1960s enhanced food production and spared the land. However, excessive use of irrigation and indiscriminate use of fertilizers and pesticides had strong adverse impacts on the environment, including depletion of SOC stock, increased risks of soil degradation by erosion and salinization, depletion and contamination of aquifers, loss of biodiversity, and emission of GHGs into the atmosphere. The number of food-insecure people may increase because of the unprecedented increase in world population, rapid economic growth, and change in diet preferences toward animal-based diets. Furthermore, the per capita cropland area is also decreasing because of growth in population, degradation of soil, urbanization, and other competing uses. Thus, the strategy is to reconcile the demand for food production with the need for restoration of soil and reduction in the environmental footprint of agroecosystems. This can be achieved by conversion to restorative land uses and adoption of proven BMPs of managing soil, water, vegetation, and livestock. The strategy is to improve soil health by restoring SOC stock, enhance the use efficiency of inputs, narrow the yield gap, and implement systems of sus-

tainable intensification of agroecosystems. The goal is to produce more from less—less land area, less water use, less input of fertilizers and pesticides, and less energy use. The much-needed paradigm shift will also need identification and implementation of appropriate policies to translate scientific knowledge into action.

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