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FEATURE

Eco-intensification through soil carbon sequestration: Harnessing ecosystem services and advancing sustainable development goals

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Land misuse and soil mismanagement, causing land trauma and severe degradation (Steinbeck 1939; Jacks and Whyte 1939; Wood 1951; Buck 2012), must be replaced by a judicious land use and prudent soil/crop/water management to restore degraded soils and improve the environment. The rapid increase in agricultural production since the 1960s has been caused by massive input of fertilizers (nitrogen [N], phosphorus [P], and potassium [K]), pesticides, energy use in plowing and other farm operations, and irrigation of about 350 Mha (8.645×10^8 ac) of land (Smil 2003; Tilman et al. 2001; Arizpe et al. 2011; Gomiero 2016). However, such an indiscriminate intensification through plowing, flood-based irrigation, and high inputs of chemicals has strong adverse effects on the quality and functionality of soil, water, air, vegetation, and biodiversity (Benson 2014). Despite these massive inputs, agronomic production of food staples has stagnated in some regions (Grassini et al. 2013), and new approaches to food production must be identified in the face of climate change (Beddington et al. 2012; Foley et al. 2011; Lal 2016a, 2018). Thus, the use of nutrients and pesticides, as well as rates and mode of application, in agroecosystems must be revisited (Drinkwater and Snapp 2007).

Advancing food security has numerous dimensions: reducing waste, improving distribution, increasing access, enhancing retention by improving human health, and increasing agronomic production. For meeting the food demand of 9.8 billion by 2050 with growing preferences for animal-based diets, it is argued that the agronomic production may have to be increased by 70% to 110% of the level in 2005 (FAO 2002; Alexandratos and Bruinsma 2012; Bruinsma 2009; Gomiero 2016), along with increase in the cropland area by as much as 150 Mha (3.71×10^8 ac) (FAO and ITPS 2015; Lambin et al. 2013). The additional demand for land resources is exacerbated by soil degradation (Oldeman 1994) and conversion to nonagricultural uses including urbanization (Lal 2017). As much as 25% of the agricultural land resources are strongly degraded (Oldeman 1994; Bai et al. 2008; Bindraban et al. 2012; FAO and ITPS 2015; Rekacewicz 2008), and the risks of additional degradation may be exacerbated by the projected climate change because of possible increase in precipitation intensities (Michael et al. 2005). Identifying systems of maintaining or improving agronomic productivity, without degrading soil fertility or polluting the environment, is an important goal especially in emerging economies (e.g., India and China). Further, soils of agroecosystems must be managed in a manner that minimizes adverse impacts on the environment. An effective erosion control, based on sound measurement techniques (Brandt et al. 2018), and prevention of soil structural degradation (Grandy et al. 2002) are important considerations. Thus, there is a need for a paradigm shift in managing soils of agroecosystems.

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Eco-intensification (EI), designed to restore soil organic carbon (SOC) and soil inorganic C (SIC) stocks of degraded soils, is an option to bring about the desired paradigm shift. Sustainable management of SOC, to maintain stocks above the threshold level of 1.5% to 2.0% in the root zone, is essential to sustaining productivity while restoring the environment. The SOC stock may be enhanced by land use and management systems that create a positive C budget in the root zone. The strategy of EI may be implemented through adoption of conservation agriculture (CA). Conversion of conventional plowing to CA (based on no-till [NT], mulch farming and cover cropping, complex rotation, and integrated nutrient management) may enhance SOC concentration and also reverse the soil degradation trends. While CA is neither a panacea nor a one-size-fits-all, the goal is to make it work for site-specific conditions because of numerous cobenefits. Thus, the objective of this article is to describe principles and techniques of EI through soil C management and sequestration, and explain technological options including importance of CA systems. This review is based on the hypothesis that the dilemma of degrading agricultural soils and increasing food demand can be effectively addressed through restoration of soil health by SOC sequestration and the attendant improvement in soil quality through the strategy of EI.

ECO-INTENSIFICATION AND CONSERVATION AGRICULTURE

EI is defined as intensification of biological processes supporting ecosystem services on medium-term (efficiency of management options) and long-term (sustainability of management option) basis (Gaba et al. 2014). A system-oriented CA (Lal 2015) encompasses a site-specific combination of (1) NT, (2) residue mulching, (3) complex rotations including cover cropping during the off-season, and (4) integrated nutrient management based on a judicious use of organic and inorganic sources of plant nutrients. The strategy is to fine-tune a site-specific system that creates a positive soil/ecosystem C budget on a long-term basis. Thus, the input of biomass-C into the soil (by residue retention, cover cropping, and amendments) must exceed the losses (by decomposition, erosion, and leaching). While decomposition of biomass is essential to maintaining the desired activity and species diversity of soil biota, losses of SOC by accelerated erosion (though water, wind, tillage, gravity, etc.) must be curtailed. Basic concepts of CA are also in accord with those of EI for "producing more from less" by enhancing the use efficiency and reducing losses (Lal 2010). The goal is to produce more per unit area of land, fertilizers and pesticides, irrigation, energy, and emission of greenhouse gases. With this strategy, the land area needed for cereal production can be decreased rather than increased (Lal 2016a).

Whereas the usefulness of CA has been recognized since the 1940s (Faulkner 1943), its adoption on about 180 Mha

(4.45×10^8 ac) of cropland (Kassam et al. 2019) is primarily limited to large-scale commercial farms in North and South America, Australia, and New Zealand. Declining soil quality (physical, chemical, and biological) and incidence of weeds are addressed in large-scale farming by inputs of agrochemicals and use of other energy-based inputs. However, lack of appropriate seeding drills and competing uses of crop residues remain to be serious obstacles to adoption of CA by resource-poor small landholders (Johansen et al. 2012). Capital and labor constraints also limit adoption of CA by small landholders (Grabowski 2011). Thus, there is a strong need to link researchers, farmers, and industry stakeholders to promote the adoption of CA (Naresh et al. 2014).

There are also concerns regarding a possibility of low crop yields and low or no accumulation of SOC by CA in degraded and depleted soils of both large and small landholder farmers. With the use of crop residue mulch and a system-based approach, however, adoption of CA by small landholders can enhance and sustain productivity under harsh conditions of rainfed farming (Rockström et al. 2009). A pertinent answer to the question of whether CA is a solution to dryland farming by small landholders is appropriately given by the positive results obtained from eastern and southern Africa (Kinyumu 2012; Araya et al. 2015; 2016) and elsewhere (Lal 2016b). Debate regarding the effects of CA on SOC sequestration and agronomic productivity (Govaerts et al. 2009; Powlson et al. 2011; Baker et al. 2007; Pittelkow et al. 2015), including the common observation that CA merely affects the distribution of SOC (stratification) in the surface layer rather than increasing its total amount (Piccoli et al. 2016), necessitates studies of a detailed soil/ecosystem C budget along with long-term measurements of SOC stocks to ~1 m (3.28 ft) depth, and adopting site-specific management systems that create a positive soil C budget. Indeed, C-input differences is the main factor explaining the variability in SOC storage in NT compared to inversion tilled systems (Virto et al. 2012).

CONSERVATION AGRICULTURE AND SOIL ORGANIC CARBON: SOME SUCCESS STORIES

There are some examples of positive results of CA on agronomic yield and SOC sequestration. In the Loess Plateau of China, Lu et al. (2018) reported a positive net ecosystem C value for a mulch-based CA system and a negative value with conventional moldboard plowing. Further, Lu and colleagues observed that conversion from plowing to CA caused SOC sequestration at the rate of 0.84 to 2.69 Mg C ha^{-1} y^{-1} (0.37 to 1.2 tn ac^{-1} yr^{-1}). In the southeastern United States, Franzluebbers (2010) observed that the rate of SOC sequestration with adoption of CA was 0.45 ± 0.04 Mg C ha^{-1} y^{-1} (0.20 ± 0.02 tn C ac^{-1} yr^{-1}). Analyzing data from long-term field experiments in the United States, Allmaras et al. (2000) reported the SOC storage in the order of NT > nonmoldboard tillage > moldboard tillage system. Based on a 24-year study conducted in southern Illinois, United States, Olson et al. (2013) reported that NT plots retained 7.8 Mg C ha^{-1} (3.48 tn C ac^{-1}) more and chisel plow –1.6 Mg C ha^{-1} (–0.71 tn C ac^{-1}) less SOC in the soil than moldboard plow. Further, the long-term productivity compared favorably with that of conventional tillage. Also, in southern Illinois, Walia et al. (2017) evaluated tillage and fertilizer management effects on SOC concentration to 1 m (3.28 ft) depth after 44 years of cultivation. Walia and colleagues observed that NT management increased SOC stocks and was even greater than that in the chisel tillage and forest soil to 1 m depth. The rate of SOC sequestration in NT for the top 15 cm (5.9 in) depth over 44 years was 0.36 Mg C ha^{-1} y^{-1} (0.16 tn C ac^{-1} yr^{-1}). Based on a 13-year study in a semiarid Mediterranean agroecosystem of Lleida, Spain, Morell (2012) concluded that SOC stock under NT increased by 4.3 and 3.9 Mg C ha^{-1} (1.92 to 1.74 tn C ac^{-1}) in comparison to minimum tillage and conventional tillage. Further, input of medium and high N fertilization increased SOC stock by 3.4 and 4.5 Mg C ha^{-1} (1.51 and 2.00 tn C ac^{-1}). A 5-year study conducted in central Morocco on three soil types (Vertisol, Cambisol, and Luvisol) by Moussadek et al. (2014) indicated that SOC concentration in 0 to 30 cm (0 to 11.81 in) depth was significantly higher in NT than conventional tillage by 10% more in Vertisol and 8% more in Cambisol, but no difference in Luvisol. The average SOC stock in 0 to 30 cm depth was 29.4 Mg C ha^{-1} (13.11 tn C ac^{-1}) under NT and 27.4 Mg C ha^{-1} (12.22 tn C ac^{-1}) under conventional tillage, an average increase of 0.4 Mg C ha^{-1} y^{-1} (0.18 tn C ac^{-1} yr^{-1}).

On a long-term basis, effectiveness of CA on SOC sequestration depends on a wide range of interacting factors including climate (especially the rainfall and its distribution) along with soil temperature regimes, soil properties, the amount and quality of the input of biomass, and the soil biodiversity. Virto et al. (2012) concluded that the C input differences may be the main factor explaining the variability in SOC storage in CA compared to inversion-tilled systems. Removal of stubble for grazing and other uses can reduce SOC stocks. Modeling studies in the state of Baden-Württemberg (southwestern Germany) by Gaiser et al. (2008) indicated the SOC sequestration rate of 0.08 to 1.82 Mg C ha^{-1} y^{-1} (0.036 to 0.081 tn C ac^{-1} yr^{-1}) in the state territory of 35,742 km^2 (13,800 mi^2). Under conventional tillage, mean SOC losses through erosion were estimated at 0.45 Mg C ha^{-1} y^{-1} (0.20 tn C ac^{-1} yr^{-1}). In the Colombian Andes, Quintero (2009) reported that SOC concentration in the whole profile was 29% higher under CA than that under conventional tillage, and that SOC sequestration especially occurred in the subsoil. Transfer of SOC in the subsoil is enhanced by the activity and species diversity of soil biota such as earthworms. Yet, there exists an urgent need to understand processes and identify appropriate management options that enhance activity and species diversity of soil biota, enhance soil health, and restore SOC stock. This is where systems of EI can play a pivotal role.

TOWARD MAKING SOIL OF AGROECOSYSTEMS A CARBON SINK

Soils of agroecosystems, croplands and pasturelands combined, cover about 5 Gha (1.24×10^{10} ac) of manageable land area for soil C sequestration (table

Table 1

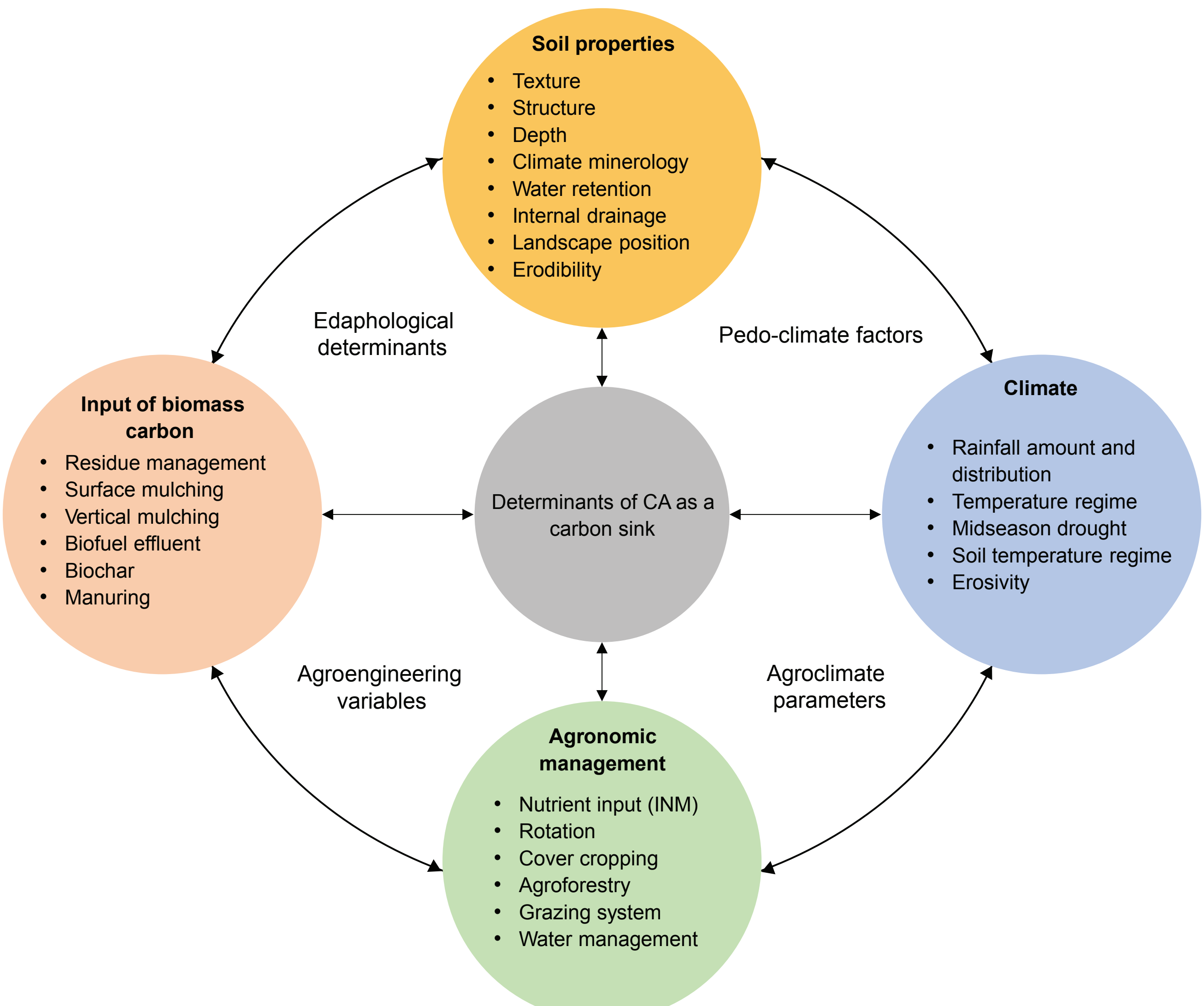
Global land use (modified from Lal [2018] and FAO [2018] publications).

Land use	Land area (10^6 ha)	Percentage of the total ice-free land area (%)
Cropland	1,590	12.0
Pasture land	3,270	25.0
Forest land (managed and natural)	4,000	30.0
Urban land	730	0.6
Other lands	4,070	32.4
Total	13,000	100.0

1). Site-specific adaptation of a system-based CA has a potential to make these soils a sink of atmospheric carbon dioxide (CO_2). Important determinants of SOC sink capacity of agroecosystems depend on numerous interacting factors (figure 1), including (1) pedo-climatic factors comprising of soil properties and climate parameters; (2) agroclimatic parameters comprising of judicious agronomic management especially that of nutrients, rotation, water, and integration with trees

Figure 1

Determinants of making soil under conservation agriculture (CA) a sink of atmospheric carbon dioxide. INM refers to integrated nutrient management based on judicious combination of organic and inorganic sources.



(agroforestry) and livestock (agropastoral); (3) agroengineering variables with regards to residues management, surface mulching, vertical mulching, application of effluent from biofuel feedstocks (i.e., Miscanthus [*Miscanthus* × *giganteus*]), and use of biochar; and (4) edaphological determinants of physical management of soil surface to reduce risks of crusting, compaction, poor aeration, and water imbalance (the drought-flood syndrome). Because there is no universal CA system, adaptation of CA to site-specific environments (biophysical and socioeconomic) is important to harness the potential SOC sink capacity.

SUSTAINABLE SYSTEMS OF ECO-INTENSIFICATION

There are notable differences in concepts, management, productivity, and environmental impact of organic farming (OF), sustainable intensification (SI), and EI (table 2). The principal strategy of SI is to increase production from existing farmland while restoring the environment (Garnett et al. 2013; Pretty 1997; Pretty et al. 2011; De Vivo et al. 2016; Tilman et al. 2011). However, innovative agroecosystems must also be pertinent to adapting and mitigating climate change, improving quality and renewability of water, enhancing biodiversity, and advancing Sustainable Development Goals (SDGs) of the United Nations. The needs for increasing food production and meeting other demands of growing and increasingly affluent world population must be met by adopting systems of land use and soil/crop/animal management that also restore quality of soil and other natural resources. Further, the meaning of the term SI is neither clear nor used in a standardized manner (Andres and Bhullar 2016; Petersen and Snapp 2016). There is also a lack of focus on improving soil health by restoring soil C (SOC and SIC) stocks through increasing inputs of biomass-C in soil. Thus, the term EI is more focused and specifically directed to improving soil health and the attendant processes (Peterson and Snapp 2016), and bringing about the much needed paradigm shift (Tchamitchian et al. 2011). Because of its relation to the environment on the one side and the human dimensions on the other (figure 2), EI is focused on restoring and sustaining soil health through improvement of soil C and strengthening its capacity for provisioning of ecosystem services.

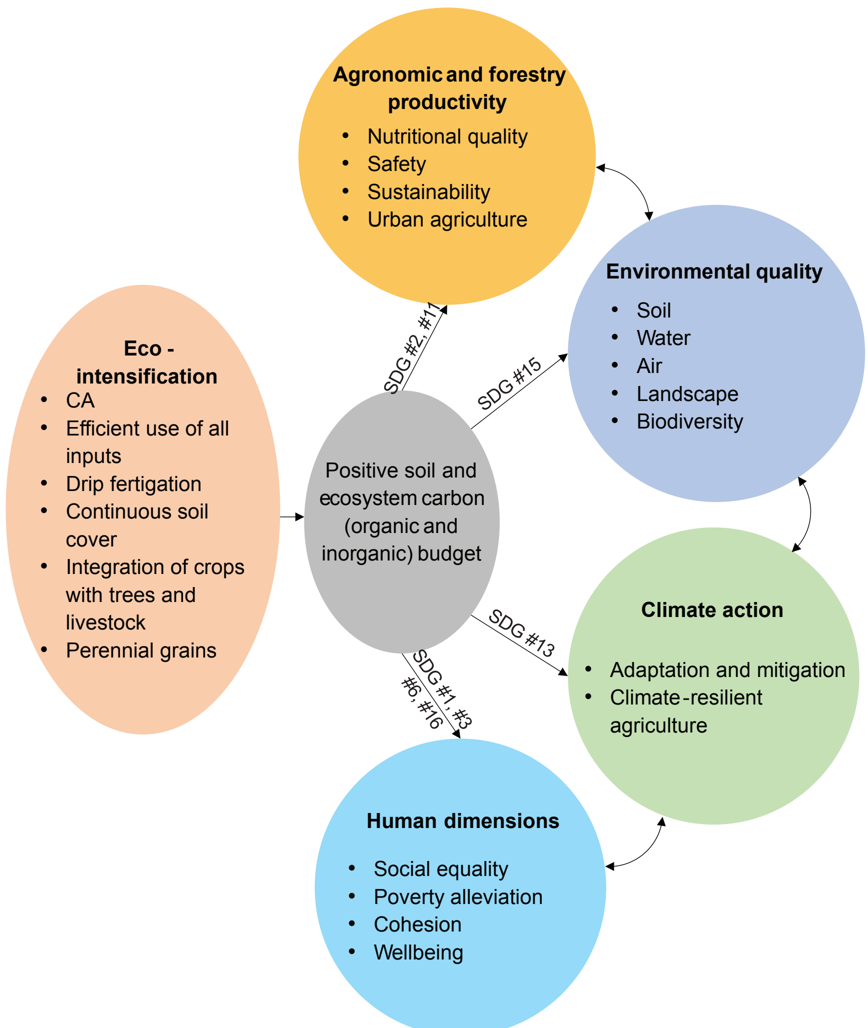
Table 2

Comparative analysis between organic farming, sustainable intensification, and eco-intensification.

Parameter	Organic farming	Sustainable intensification	Eco-intensification
Fertility management	Managing soil organic matter, enhancing soil biological activity, biological nitrogen fixation (BNF)	Using chemical fertilizers	Integrated nutrient management based on a judicious combination of organic and inorganic sources, biomass recycling, and BNF
Disease and pest management	Crop rotations, natural predators, resistant varieties, diverse cropping systems	Chemical pest control: herbicides, fungicides, insecticides	Integrated pest management, creating disease suppressive soils, judicious chemical intervention, and enhancing biodiversity
Seedbed preparation	Mechanical tillage for weed control, residues incorporation, and manure management	No-till based on chemical weed control	Conservation agriculture based on a system approach: (1) residue mulch, (2) no-till, (3) complex rotations, (4) cover cropping, (5) integrated nutrient management
Water management	Soil-water conservation	Supplemental irrigation, drip-fertigation	Soil water conservation, minimal supplemental irrigation, resilience against drought-flood syndrome
Environment management	Strengthening biodiversity, minimizing chemical release	Minimal biodiversity	High soil biodiversity, good soil health, better environment quality
Risks of soil degradation and pollution	No soil pollution but high risks of soil erosion because of mechanical tillage	High risks of soil pollution by chemicals	Conservation-effective with minimal risks of soil degradation and environmental pollution
Agronomic yield	Low	High but not sustained	Optimal but sustained with creation of better environment and regreening of landscape
Gaseous emission	Low	Very high	Moderate and often emission-negative
System approach	High diversity of crops, integrated with trees and livestock	Improved varieties grown with high input of fertilizers and supplemental irrigation	Integrated soil-crop-livestock-tree systems to enhance soil and environmental health by using conservation agriculture and sequestering carbon

Figure 2

Eco-intensification of agroecosystems for harnessing ecosystem services and advancing Sustainable Development Goals of the United Nations: #1 no poverty; #2 zero hunger; #3 good health and wellbeing; #6 clean water and sanitation; #11 sustainable cities; #13 climate action; #15 life on land; and #16 peace, justice, and strong institution.



The goal of OF is to eliminate the use of chemicals; it has its niches, but also limitations (table 2). However, EI is not limited to OF per se. The strategy of EI involves judicious use of inputs (both organic and inorganic) to meet the soil/farming system demands for nutrients, water, and pest control. The impact of EI goes beyond increase in agronomic productivity. The latter can be achieved by genetic engineering and biotechnology on a short-term basis (South et al. 2019), but it cannot be sustained unless soil health and water quality are also enhanced. Neglecting soil and water resources and increasing productivity through plant improvement alone has and can create serious environmental hazards. In contrast, EI in conjunction with improved germplasm is a real paradigm shift because it also minimizes the risks of environmental degradation. Adoption of EI is critical to enhancing soil quality/health (Bünemann et al. 2018) and to developing climate-resilient systems against the drought-flood syndrome. Excessive and indiscriminate use of chemicals, leading to pollution, contamination, and eutrophication, must be avoided. Thus, EI implies harnessing of ecosystem services (Bommarco et al. 2013) while restoring soil resources, mitigating gaseous emissions from agroecosystems (Burney et al. 2010), and sustaining productivity. The need for a paradigm shift in agroecosystems (Fedoroff et al. 2010) can be met through EI (Hochman et al. 2013) by farming for ecosystem services (Robertson et al. 2014) while advancing the SDGs (figure 2).

CONCLUSION

Soils of agroecosystems are an important sink of atmospheric CO_2. With the necessity of limiting the global warming to 1.5°C (2.7°F) and restoring the environment, the strategy is to manage soils of agroecosystems to harness ecosystem services while restoring the environment and advancing SDGs of the United Nations. The needed paradigm shift in agriculture can be met through adoption of the strategy of EI, which implies managing soils of agroecosystems to be climate-resilient by adapting and mitigating anthropogenic climate change, improving quality and renewability of water, enhancing biodiversity, improving human wellbeing, and conserving nature. There are notable differences in concepts, practices, and soil/environmental impacts among OF, SI, and EI. The latter involves the concept of producing more from less while restoring soil health and improving the environment. Examples of farming practices for adopting EI include CA, perennial culture, and integration of crops with livestock. Because CA may neither always produce the desired yield nor sequester soil C, fine-tuning based on a soil-guide and techniques that create a positive soil/ecosystem C budget (e.g., cover cropping and earthworm activity) must be identified. The goal is to adapt the CA system and make it work because of its numerous cobenefits. While OF has its niches, EI implies a judicious/prudent use of all inputs (organic and inorganic), improving use efficiency and reducing their leakage into the environment.

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