Renewable Agriculture and Food Systems: 28(2); 102–114 doi:10.1017/S1742170512000452

Enhancing ecosystem services with no-till

R. Lal

Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, 2021 Coffey Road,
The Ohio State University, Columbus, OH 43201-1085, USA.
Corresponding author: lal.1@osu.edu

Accepted 11 December 2012; First published online 11 March 2013 **Review Article**

Abstract

Ecosystem functions and services provided by soils depend on land use and management. The objective of this article is to review and synthesize relevant information on the impacts of no-till (NT) management of croplands on ecosystem functions and services. Sustainable management of soil through NT involves: (i) replacing what is removed, (ii) restoring what has been degraded, and (iii) minimizing on-site and off-site effects. Despite its merits, NT is adopted on merely ~9% of the 1.5 billion ha of global arable land area. Soil's ecosystem services depend on the natural capital (soil organic matter and clay contents, soil depth and water retention capacity) and its management. Soil management in various agro-ecosystems to enhance food production has some trade-offs/disservices (i.e., decline in biodiversity, accelerated erosion and non-point source pollution), which must be minimized by further developing agricultural complexity to mimic natural ecosystems. However, adoption of NT accentuates many ecosystem services: carbon sequestration, biodiversity, elemental cycling, and resilience to natural and anthropogenic perturbations, all of which can affect food security. Links exist among diverse ecosystem services, such that managing one can adversely impact others. For example, increasing agronomic production can reduce biodiversity and deplete soil organic carbon (SOC), harvesting crop residues for cellulosic ethanol can reduce SOC, etc. Undervaluing ecosystem services can jeopardize finite soil resources and aggravate disservices. Adoption of recommended management practices can be promoted through payments for ecosystem services by a market-based approach so that risks of disservices and negative costs can be reduced either through direct economic incentives or as performance payments.

Key words: natural capital, carbon sequestration, nutrient cycling, erosion control, residues management, biodiversity, food security, climate change

The importance of the moldboard plow, in conjunction with the use of tractors and mechanization of farm operations, in expanding the land area under cultivation and increasing farm productivity is of historical significance. However, the vulnerability of plowed soil to accelerated erosion, compaction, oxidation of soil organic matter, emission of greenhouse gases (especially carbon dioxide) and other environmental issues (i.e., loss of soil biodiversity) led to the development of no-till (NT) farming.

Keen[1] observed that the benefits of plowing were mostly attributed to weed control. The rationale of plowing was questioned by Faulkner[2,3] because of serious erosion during the Dust Bowl era, even when herbicides were not yet available. Despite the intense debate on plowing[4] or not[2,3], it was the discovery of herbicides after World War II that made NT farming a practical reality. Indeed, NT farming evolved in the late 1950s and early 1960s primarily to reduce risks of accelerated soil erosion[5,6] and non-point source pollution from row cropping in the US Corn Belt[7–14]. Experiments on direct drilling in Europe started in the early 1970s with the availability of paraquat[15]. The historical roots of moldboard plowing, which cuts and turns over the soil, lie in a gradual replacement of the ard (a scratch tool or a modified v-shaped stick) by a metallic tool during the 7th century[16,17]. The ard, developed for alluvial soils of arid and semi-arid climates of the Fertile Crescent and valleys/flood plains of the Indus and Nile, was not a suitable tool for the humid climates and fine-textured soils of northern Europe. Thus, the moldboard plow gradually replaced the ard. The moldboard plow used in the US was designed by Thomas Jefferson in 1784, patented by Charles Newfold in 1796, and marketed in the 1830s as a cast iron plow by a blacksmith named John Deere[16].

Any system that eliminates all pre-seeding seedbed preparation is called NT or direct seeding. Three principal components of NT farming are: (i) elimination of all pre-seeding tillage (i.e., primary, secondary and tertiary), (ii) retention of crop residues, and (iii) control of weeds by

Table 1. Estimates of land area under conservation agriculture (adapted from Kassam et al.[25] and Friedrich et al.[26]).

	Land area (10^6 ha)	
Year	**World**	**South America**
1973–77	2.7	0.06
1978–82	2.7	0.2
1983–87	6.3	0.7
1988–92	11.4	1.4
1993–97	35.0	9.0
1998–02	66.8	19.9
2003–07	100.3	27.6
2008–09	106.5	27.9
2010–11	124.8	55.4

herbicides. Weed control is a major challenge, especially in soils of the tropics, in the presence of perennial weeds and for organic farming. Thus, use of cover crops and residue mulch is a strategic option. Establishing an aggressive cover crop can smother weeds, while improving soil structure, nutrient cycling and availability. Soil and water conservation, specifically erosion control, has been the principal advantage of stubble mulch[18,19] and NT farming[7,8,20–24]. The concept of NT farming was expanded during the 1990s to conservation agriculture, which is comprised of five components: (i) elimination of pre-seeding tillage, (ii) adoption of complex crop rotations, including cover crops and agroforestry, (iii) use of integrated nutrient management strategies, (iv) control of weeds and other pests by integrated pest management, and (v) conservation, harvesting and recycling of water.

Globally, NT farming has been adopted in about 125 million hectares (Mha) out of a total of 1500 Mha of cropland area (Table 1)[25,26]. The rate of adoption was very high during the first decade of the new millennium in commercial and large-scale farms of South America (Table 1). In turn, conservation agriculture in the 1990s evolved into sustainable land management during the 2000s. Sustainable land management is defined as a knowledge-based combination of technologies, policies and practices that integrate land, water, biodiversity and environmental concerns (including input and output externalities) to meet rising food and fiber demands, while sustaining ecosystem services and livelihoods[27,28]. Five components of sustainable land management are: (i) adoption of conservation agriculture principles, (ii) adoption of a judicious land use, (iii) adaptation to climate change, (iv) mitigation of climate change, and (v) enhancement of soil/ecosystem resilience.

Ecosystem Services

Ecosystem functions refer to the habitat, biological, or system properties or processes of ecosystems. Ecosystem goods (i.e., food) and services (i.e., water filtration and pollution abatement) refer to the benefits that humans derive from ecosystem functions[29,30]. Specifically, ecosystem services are the conditions and processes through which natural ecosystems sustain and fulfill human demands[31]. Principal ecosystem services, outlined in Fig. 1, include provisional (food, feed, water, etc.), moderatory (climate stabilization, water filtration, pollutant denaturing, etc.), ecological (elemental cycling, biodiversity, etc.), and aesthetical and cultural (recreational, spiritual, etc.)[32–34]. Numerous ecosystem services essential to human wellbeing are provided by the soil. However, there are important trade-offs and synergies that need to be objectively considered[35].

Soil is a four-dimensional (length, width, depth and time) geo-membrane at the lithosphere/atmosphere interface that is a medium for plant growth and moderator of all ecological processes essential to functioning of terrestrial and associated aquatic processes. Depending on the predominance of specific soil-forming factors[36,37], soils provide a range of ecosystem services across the landscape. Soil quality, defined as the capacity to perform ecosystem functions, depends on the activity and species diversity of soil biota, which transforms and recycles matter and energy. A gram of fertile soil may contain millions of microorganisms, including protozoa, algae, fungi and numerous other known and unknown species. Major ecosystem services of a soil are generated by numerous biogeochemical cycles driven by solar and chemical energy and operating at different scales, ranging from global (carbon, nitrogen and water cycles) to molecular (chemical transformations).

Land use and management strongly impact soil's ability to provide ecosystem services. Conversion of land from natural systems to agroecosystems, a necessity to support the human population and its ever-increasing demands driven by growing affluence, can provide, but also curtail, numerous ecosystem functions and services. Therefore, a sustainable strategy must be to minimize the adverse impacts of land-use conversion for production of feed, food, fiber, fuel, and other goods and services to meet human demands. It is precisely in this context that widespread, but prudent adoption of NT farming, conservation agriculture (CA), and sustainable land management can play a pivotal role.

Natural Capital of Soil and Ecosystem Services

Sustainable use of finite soil resources necessitates a thorough understanding of the role of soil processes in relation to ecosystem functions, including but not limited to human wellbeing. In this context, Robinson et al.[38] proposed the concept of 'natural capital' of soil within the framework of ecosystem services. A clear distinction in the use of terms is essential, because many terms have multiple definitions[39]. The term 'natural capital' is an

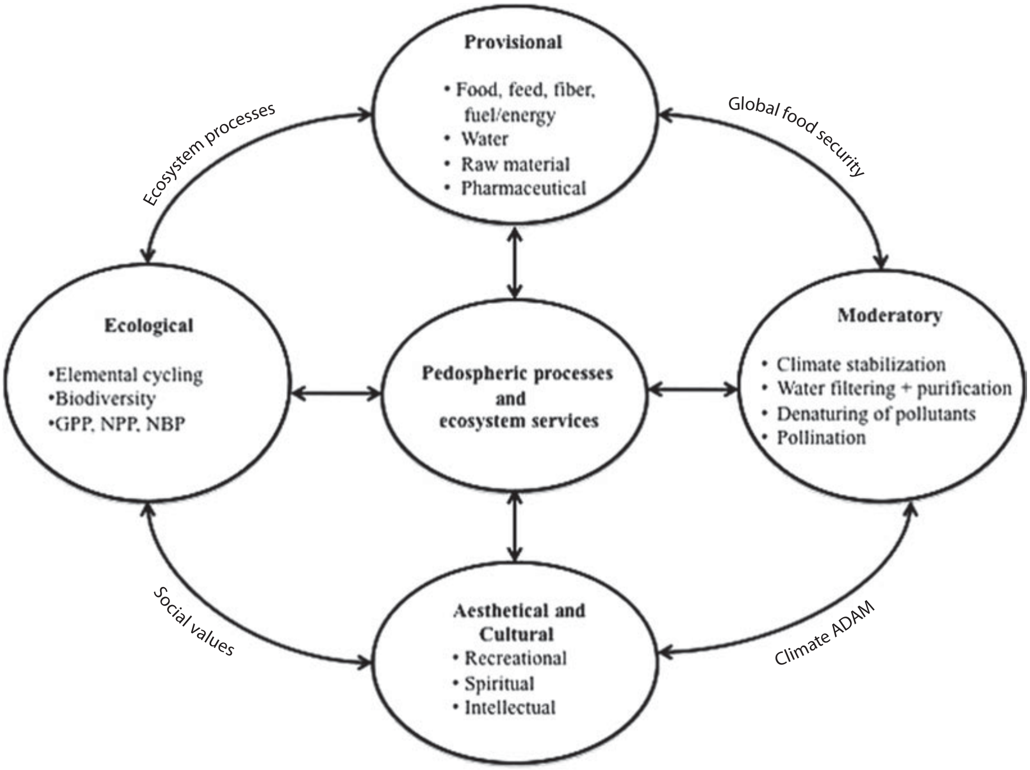

Figure 1. Types of ecosystem services.

extension of the economic idea of manufactured capital to include environmental goods and services. As an analogy, natural capital of soil would consist of its properties such as clay and soil organic matter contents, soil depth, water retention capacity, etc. Thus, ecosystem services from soil would include tangibles such as net primary production, agronomic yield, climate moderation through carbon sequestration, methane oxidation, etc. Accordingly, Robinson et al.[38] proposed that principal components of soil's natural capital would include: (i) mass (solid, liquid, and gaseous), (ii) energy (thermal), and (iii) organization or entropy. All three components have quantitative and qualitative attributes. Furthermore, sustainability of agroecosystems depends on strategic management that integrates the natural capital of soil across different scales from molecular to global. These are among several major ecological challenges that must be scientifically addressed[40]. Furthermore, apparent conflict among ecosystem services (i.e., food versus fuel and agronomic productivity versus biodiversity) must also be resolved. For example, mandating the use of biofuel in one place may increase emission of greenhouse gases at another due to land-use changes[41]. Implementation of 'The Billion-Ton Biofuels Vision'[42] contradicts the use of NT technology, because cellulosic ethanol production may require removal of residues from croplands. It is also debated whether food security and biodiversity are mutually exclusive goals[43]. These conflicts may be addressed through 'ecological intensification' based on the use of biological regulation to manage agroecosystems at field, farm and landscape scales[44]. In this context, natural ecosystems may provide examples of a number of interesting properties that could be incorporated into agroecosystems. Monitoring and assessment of sustainable land management as tools to promote sustainable use of soil resources are widely promoted by development organizations (World Bank and FAO) and bilateral programs (USAID)[45].

Soil degradation, i.e., a decline in the capacity of a soil to maintain ecosystem functions, is an important factor in evaluating ecosystem services and remains a major global issue[46]. Divergent views of agronomists and social scientists about the impact of degradation on ecosystem services must be resolved[47]. Apparent divergence in opinion and approaches is based on two contrasting views of increasing human population versus limited natural resources: (i) the Boserupian[48–50] view emphasizing the significance of human ingenuity in addressing ecological problems, and (ii) the Malthusian view reiterating that resources are finite and population increase can lead to degradation of natural resources. Drechsel et al.[51] surmised through analyses of data from 36 countries in sub-Saharan Africa that Malthusian mechanisms indeed are at work and are leading to soil nutrient depletion, accelerated erosion and reduced fallow periods caused by population pressure. This view illustrates the unsustainable population–agriculture–environment nexus on the African continent. The issue of severe decline in fertility of soils of Africa was also pointed out by Sanchez[52], as well as of global soil degradation by Bai et al.[46]. Should the

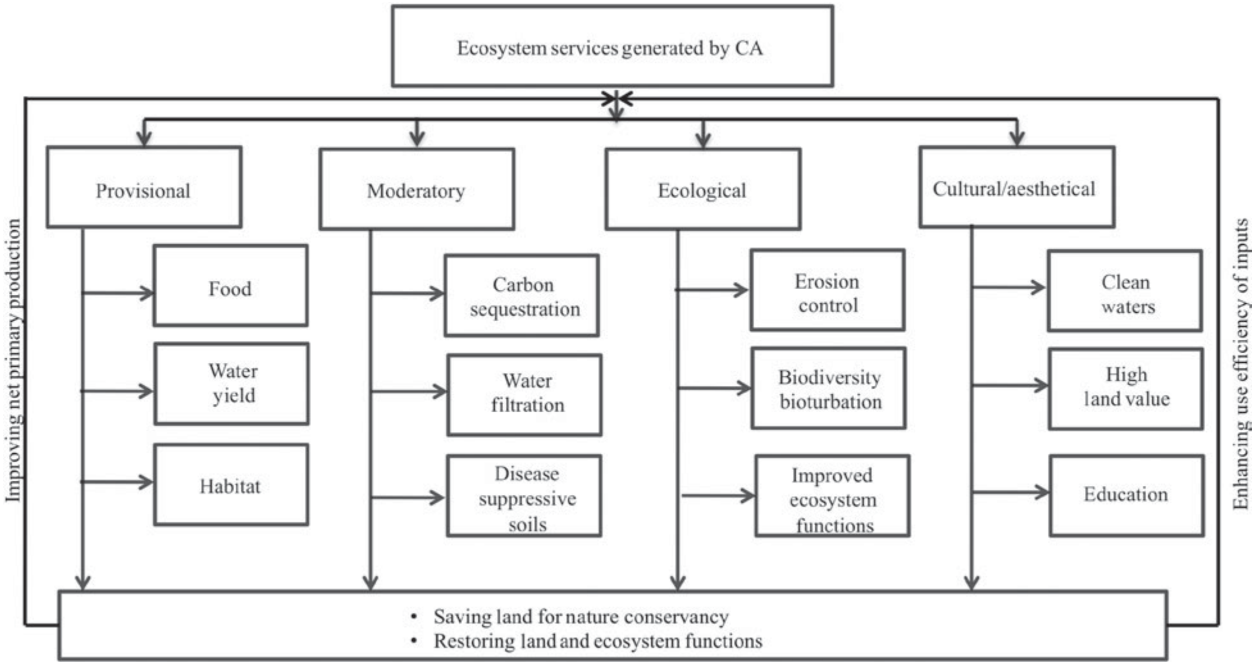

Figure 2. Range of ecosystem services generated by conservation agriculture (CA).

Boserupian view be considered sound, agricultural scientists and policy makers urgently need to identify and implement successful strategies to overcome current challenges. Difficulties encountered in implementing such strategies without effective community participation could exacerbate soil degradation and desertification[53]. Thus, Hurni[54] and Hurni et al.[55] proposed adoption of NT farming approaches with due consideration of social and economic dimensions of land-related issues.

Adoption of sustainable soil management technology can address these issues. Principal requirements of sustainable soil management are: (i) maintaining soil organic carbon (SOC) concentration at a level above the critical threshold in the root zone, (ii) optimizing soil physical quality including structure and water retention/transmission characteristics, (iii) managing plant nutrients, (iv) enhancing favorable soil biological properties, (v) improving root growth and proliferation, and (vi) reducing risks of soil erosion and other degradation processes[56]. Most of these requirements are met with a judicious and continuous use of NT for a long period (Fig. 2). Conversion to NT is especially useful in restoring/sustaining soil physical quality and reducing risks of water runoff and soil erosion, as indicated by soil bulk density, SOC dynamics, root growth, tilth, friability and hard-setting[57,58].

Ecosystem Services and Conservation Agriculture

By mimicking nature, discriminate and judicious implementation of NT can generate essential ecosystem services to meet specific demands of the growing human population, while also reducing risks of soil and environmental degradation. Principal ecosystem services provided and sustained through a long-term adoption of NT are discussed below.

Food security

Efficient use of inputs and agronomic productivity can be greatly enhanced by improving the concentration of SOC to optimal levels covering a wide range of crops and soils[59–63]. Enhancement of SOC to an optimum level increases crop yield by: (a) increasing plant available water capacity and nutrient supply (macro and micro) by promoting recycling and reducing losses, (b) restoring soil structure and tilth by bioturbation and microbial processes, and (c) decreasing soil erodibility and increasing water infiltrability, thereby reducing the risks of runoff and accelerated erosion. Despite notable improvements in soil quality, agronomic response to restoration of SOC in the root zone depends on a multitude of factors, including soil moisture and temperature regimes, availability of macro- and micro-nutrients, and various other soil properties[64,65]. Syntheses of global data from field experiments have shown a corresponding increase in yields of a variety of crops with an incremental increase in SOC in the root zone[64–66]. In general, low agronomic yields from degraded soils of sub-Saharan Africa, South Asia and other regions where SOC has been severely depleted by perpetual use of extractive farming are attributed to severe curtailment of beneficial rhizospheric processes in soil.

Improvement in the soil quality and resilience through restoration of SOC can also enhance adaptation of agricultural and food systems to climate change. Enhancing water-use efficiency and crop yield through an increase in SOC is one adaptation strategy. Increasing water-use efficiency[67] is crucial to harnessing the benefits of an increase in atmospheric carbon dioxide concentration, or the so-called carbon dioxide fertilization effect. Water-use efficiency can be specifically improved in dryland farming by adopting NT systems[68].

Climate moderation

In view of the lack of appropriate metrics to account for emission of greenhouse gases within a land-use system, Anderson-Teixeira and DeLucia[69] proposed the concept of Greenhouse Gas Value. It accounts for potential greenhouse gas release upon conversion of a vegetation cover, annual greenhouse gas flux, and the projected greenhouse gas exchanges caused by land-use conversion and management. Greenhouse Gas Values provide a quantitative index of the emission-related consequences of any land use and management decision. Conversion of plow tillage to NT can enhance SOC concentration and stock[70–73] by reducing runoff, erosion and mineralization of soil organic matter. In South Africa, Mchunu et al.[74] observed that topsoil SOC stock was 26% higher under NT than under plowed soil, while NT reduced soil loss by 68% and SOC loss by 52%. However, the assessment of net gains in SOC must also consider the hidden C costs of inputs (such as fertilizers, pesticides, irrigation and other farm operations)[75]. In most cases, there is an increase in SOC concentration in the surface layer of soil managed by NT for a long time. However, there have been examples of lower concentration of SOC in the sub-soil layers of land managed with NT compared with that by plow tillage[76–78]. Determining differences in the accrual of SOC stock among tillage systems must be evaluated on a whole-profile basis rather than in the surface layer alone[77], and the experimental design must also use an adequate number of replications[79]. Over and above the effect of tillage methods and crop-residue management, SOC retention is also influenced by water management and irrigation system[80]. However, further increase in temperature under changing climate may decrease SOC[81], regardless of tillage system.

In general, adoption of NT on degraded agricultural lands has the potential to sequester SOC, while building fertility and restoring soil functions[82]. In addition to SOC (and carbon dioxide) dynamics, there are questions about other greenhouse gases (i.e., nitrous oxide and methane), which are also affected by tillage systems. In some soils, NT can lead to increased emission of nitrous oxide[83–85]. Irrespective of tillage, however, emission of nitrous oxide is highly variable and rates differ between arid and humid climates and fine- and coarse-textured soils. Smith et al.[86] observed that nitrous oxide emission from under corn (*Zea mays*) was the lowest from a precision-tillage treatment ($2.4\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$) compared to conventional tillage ($4.9\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$) or with cover crop ($5.0\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$). Precision tillage involved additional farm operations to modify the seedbed. Impact of a cover crop on nitrous oxide emission can be highly variable, and some studies have shown reduced emission from systems with cover crops[87]. The issue of high spatial variability in nitrous oxide emission is an important consideration[88]. Depending on soil type and management, nitrous oxide emission can also be greater from plow tillage than from NT[89,90]. High stratification of SOC under NT along with enhanced bioturbation can lead to improvements in soil structure and tilth. A NT-managed soil with good structure can oxidize methane and make the NT system a net sink for atmospheric methane[91].

With the high global warming potential of methane and nitrous oxide, it is important to quantify the full greenhouse gas effects of land use and soil management systems[69,92]. Therefore, a complete life cycle assessment of greenhouse gas emissions is appropriate[93]. Whereas NT can play an important role in building a climate-resilient farm, the role of associated components (i.e., water, energy, fertilizers, residues and cover crops) must also be considered[94]. Residue management (burning/removal or incorporation) can also impact the greenhouse gas budget of a farming/cropping system[93].

While conservation management of world soils has a large technical potential to sequester SOC and offset anthropogenic emissions[95], there are numerous challenges to realizing this potential[96]. In general, challenges posed by humans (e.g., land rights, social equity and cultural traditions) are often more severe than those posed by biophysical constraints (e.g., soil type, climate, terrain and slope gradient).

Biodiversity

Soil is an important habitat for biota. Soil organisms, comprising an extremely diverse and complex biological community, are affected by land use and soil management systems[97]. A strong link exists between biodiversity and human wellbeing[98]. Thus, habitat needs for other species must not be jeopardized in a managed ecosystem[99]. Soil biota generate numerous ecosystem services, such as elemental cycling, denaturing of pollutants, soil aggregation, and insect and disease control[100–107]. While agricultural intensification generally decreases biodiversity[108], adoption of NT enhances biodiversity and strengthens soil functions and ecosystem services[109]. In strong contrast to NT, plow tillage can diminish microbial biomass and enzyme activity[110]. Thus, to enhance biodiversity, a NT farming system will be better than one with plow tillage. In general, NT has the potential to diversify the suite of ecosystem services through judicious management[111], notably less soil disturbance. Specific indicators of biodiversity are needed for croplands in diverse biomes[112]. It may be appropriate to assess biodiversity

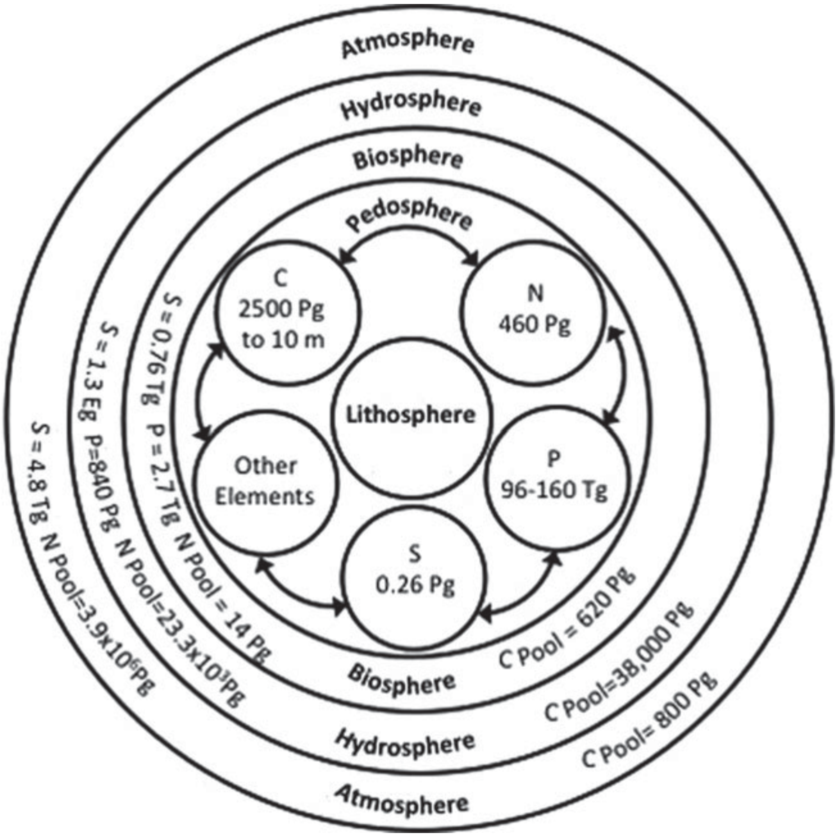

Figure 3. Schematic of the coupled cycling of elements within the pedosphere. Fluxes of elements in the pedosphere with those in the biosphere, hydrosphere and atmosphere are well known[115]. Data on carbon pools are from Lal[91]. Data on nitrogen pools are from Robarts and Wetzel[116] and those of P and S are from Stevenson[117].

in multi-functional landscapes[113], and species identity may be even more important than species diversity[114].

Elemental cycling

The earth/soil has numerous elements with their own cycles, either singularly or coupled. Coupled cycling of elements is the rule, rather than an exception. Major elements (carbon, nitrogen, phosphorus and sulfur) have coupled cycling within the pedosphere, and among the pedosphere, lithosphere, atmosphere, hydrosphere and biosphere through an inter-connected web of global cycles (Fig. 3)[91,115–117]. By conserving carbon and water, NT strengthens the coupled cycling of numerous elements. Coupled cycling of carbon and water at a global scale indicates the inter-dependence of these elements (Fig. 4)[91,95,118–121]. Within a landscape, long-term use of NT strengthens elemental cycling. For example, NT stratifies SOC by concentrating it within the surface layer, conserving water by reducing runoff and evaporation, increasing water storage in the root zone, increasing plant-available water capacity, and increasing net primary production by reducing risks of drought and decreasing losses of plant nutrients by runoff, leaching and erosion. The return of crop residues to soil, an integral component of NT, is crucial to elemental cycling and reducing the requirement for nutrient replenishment with chemical fertilizers.

Soil erosion, sedimentation and non-point source pollution

Surface mulch on unplowed and consolidated soil decreases erodibility, increases resilience and drastically reduces erosivity (e.g., rain drop impact, shearing force of overland flow and blowing wind, and wind-driven rain). Data in Table 2 from the North Appalachian Experimental Watersheds at Coshocton, Ohio, indicate the relative effectiveness of NT farming in erosion control, especially for some exceptional rainstorm events[122]. Data in Table 3 from western Nigeria also show the effectiveness of NT in reducing runoff and soil erosion up to a slope gradient of 15% in an environment characterized by highly erosive tropical rains[123].

Despite the conservation effectiveness of NT, it does have some disservices. Surface applications of fertilizers and pesticides/herbicides can accentuate the risk of transport in runoff, especially during the first few events after application[124–126]. In Ohio, risk of herbicide transport in water runoff was high for an erosive rainfall event that occurred within 10 days of application, and detectable levels could be observed 50–60 days after application. Shipitalo et al.[127] observed concentration of atrazine and alachlor in runoff high enough to be of concern even for NT, and concentration of herbicides in the first few runoff events after application can be well

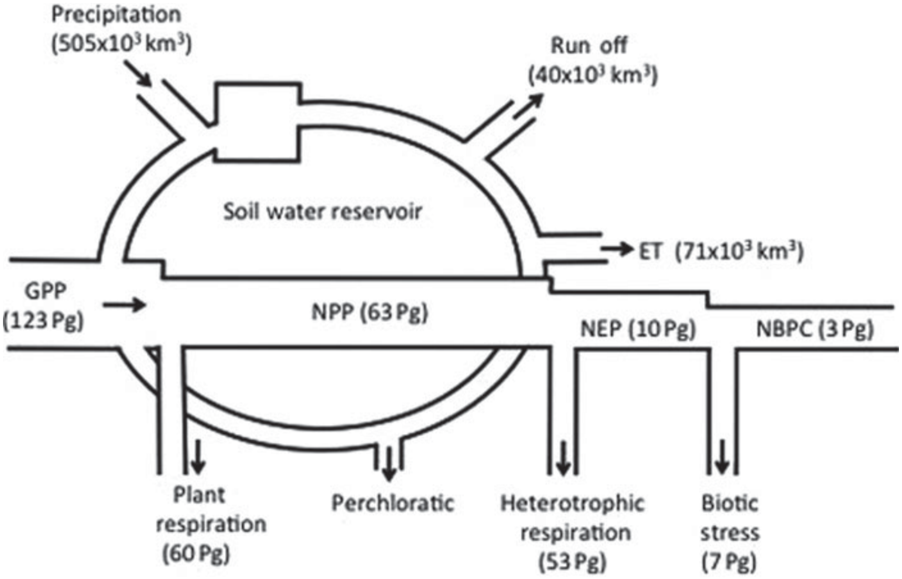

Figure 4. Schematic of the coupled cycling of carbon and water. Data for C fluxes are from multiple sources[91,95,118,119] and those for water are from Ogle et al.[120] and Bengtsson[121].

Table 2. No-till effects on soil erosion from cropland watersheds at Coshocton, Ohio[116].

Tillage system	Length of record (years)	Soil erosion ($\mathrm{Mg\,ha^{-1}\,yr^{-1}}$)	Ratio
Conventional (prevailing)	28	11.57	578.5
Improved	22	3.23	161.5
Minimum tillage	10	0.87	43.5
No-tillage	5	0.02	1

Prevailing: straight/sloping rows, low fertility.
Improved: contour rows, moderately high fertility.
Minimum tillage: plow and plant.
No-tillage: chemical weed control, corn stover mulch, manure.

above drinking water standards. In addition, flow of pesticide-containing water through macropores and preferential pathways can be an issue with NT systems[128]. If an intense rainstorm were to occur soon after surface application of chemicals to soil with well-developed macroporosity, water transmitted into tiles and shallow ground water by macropores could contain significant concentration of chemicals[129].

Conservation Agriculture and Relationship among Multiple Ecosystem Services

Strong links exist among diverse ecosystem services, but managing exclusively for one (i.e., food production) can lead to a substantial decline in another (i.e., biodiversity). Therefore, it is important to understand theoretical relationships among ecosystem services. Bennett et al.[130] proposed three sets of issues to understand relationships among ecosystem services: (i) nature of ecosystem service (i.e., flow across a landscape or specific processes that regulate the nature of the relationship), (ii) trade-offs and synergism (i.e., effective ways to mitigate trade-offs or change of relationship among ecosystem services over time, with management and across scales), and (iii) regulating services and regime shift (i.e., nature of shifts or variation in ecosystem services with decline in regulating services). Trade-offs may occur among ecosystem services, and specific disservices in agroecosystems must be carefully evaluated at appropriate temporal and spatial scales, since the negative impacts are difficult to reverse (i.e., erosion, non-point source pollution)[35]. Trading ecosystem carbon storage for food[131] has important managerial implications that require an objective and careful evaluation. Thus, agricultural ecosystems must be appropriately managed to optimize diversity, composition and functioning of remaining natural ecosystems in the landscape[132]. In some cases, adoption of organic agriculture may strengthen specific ecosystem services such as pollination, biological control and nutrient cycling[133]. Yet, low productivity of organic systems is an issue in the world with an ever increasing population and escalating demand for ecosystem services.

Payments for Ecosystem Services

Innovative agricultural systems must be developed to maximize ecosystem function and services and minimize disservices. Therefore, linkages and inter-dependence between food production and other ecosystem services for recommended management practices must be critically assessed. Adoption of recommended management practices by land managers, especially resource-poor

Table 3. Mulching effects on surface runoff and soil erosion from an Alfisol in western Nigeria from April to August 1973 (recalculated from Lal[123]).

	Runoff (mm/season)					Erosion (Mg ha^{-1})				
Slope gradient (%)	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
1	316	0	55	1	20	7.5	0	1.2	0	0.6
5	347	7	159	2	81	80.4	0	8.2	0.2	5.6
10	311	20	52	20	51	152.9	0.1	4.4	0.1	3.2
15	317	17	90	21	46	155.3	0	23.6	0.1	7.6
Mean	323	11	89	11	50	99.0	0.025	9.4	0.1	4.25
Ratio	29	1	8	1	5	3960	1	376	4	170

Rainfall = 781 mm.
1 = Plowed fallow, 2 = corn, plowed, mulched, 3 = corn, plowed, 4 = corn, no-till, 5 = cowpea, plowed.

farmers, can be promoted through payments for ecosystem services (i.e., carbon sequestration, water resources, improvement and biodiversity enhancement). Establishment of a rational price (i.e., carbon credits or green water credits) may require identification of soil/site-specific indicators[134] at different spatial scales and with hierarchical perspective. These indicators can provide the basis of an appropriate framework. High negative external costs associated with food production[135] could be minimized through the use of appropriate indicators. One option would be to determine suitability of a provision by collective management or cooperative solution based on resource characteristics[136]. Another option would be to reduce disservices and negative costs through payments for enhancing ecosystem services and reducing disservices. A third option would be a market-based approach[137].

Market-based approaches could reduce risks of the 'tragedy of the commons'. The strategy would be to harness market potential to provide ecosystem service incentives to land managers. Markets could be used as a tool for organizing the supply of ecosystem services to and from agroecosystems[137]. Being myopic by nature, humans' desires to make quick economic gains by cutting corners could degrade soils and jeopardize natural resources. Thus, assessing societal value of ecosystem services would be relevant, especially in developing countries[138] with predominantly resource-poor farmers and smallholders. A just pricing system for ecosystem services could promote the adoption of NT and recommended management practices.

A market-based tool could be used either as: (i) economic incentive or (ii) performance payment[139]. The latter, paid in cash or kind, could be made conditional on achieving a well-defined action or outcome. For example, carbon credits could be sold only if farmers were to adopt and maintain NT for a specific duration of time (e.g., 6–10 years), and payments could be made at the end of the designated period. Determining the rational value of a specific ecosystem service would be critical to the success of the program. Undervaluing a service (such as SOC sequestration) could lead to its misuse and depletion. No one protects or safeguards an under-valued resource. The market-based approach for voluntary carbon trading was not successful, because of the unfair price governed by the lack of cap on fossil fuel combustion. However, payments to farmers for providing essential ecosystem services (e.g., adapting and mitigating abrupt climate change, improving water quality and its renewable supply, and enhancing biodiversity) based on a fair and just price would incentivize land managers toward adoption of sustainable technologies.

Constraints to Adoption of No-till

Despite numerous advantages, cropland area under NT is hardly 9% worldwide, mostly in countries where large-scale commercial farming is practiced (e.g., USA, Canada, Brazil, Argentina, Chile, Paraguay and Australia). Adoption of NT is practically negligible by resource-poor, smallholders of sub-Saharan Africa, South and South-East Asia, Central America, Caribbean and Pacific Islands. Yet, these are also the regions where the potential benefits of NT are high[140]. Reasons for low adoption of NT vary among developing and developed economies, climatic regions, soil types and farming systems. In developing economies, farmers may not have access to herbicides and appropriate seeding equipment. Competing uses of crop residues for fodder and fuel may be another constraint. Land ownership and tenure, important to investment in long-term improvement in soil restoration, is another issue that limits adoption. Furthermore, NT farming may require more skills and experience in its implementation.

In temperate regions, spring-time soil temperature is often sub-optimal and seedling emergence and crop establishment are slower under NT compared with plow-based seedbed preparation. Thus, crop yield can be depressed under colder, wetter climates[120,141]. Nonetheless, intensified rotations with NT in the US Great Plains can be more profitable than plow-based systems, even when grain yields are slightly lower[142]. However, even a slight yield decrease may be perceived as risky to farmers. There is also a range of socio-cultural/economic reasons for low adoption of NT[143].

Conclusions

Ecosystem services providing benefits to the environment must be sustained to meet the increasing and diverse demands of humanity. Soil provides all four categories of ecosystem services (e.g., provisioning, moderating, ecological and cultural/aesthetical) and its resource must be sustainably used and restored, because it is a finite resource and prone to degradation and depletion. Sustainable management of soil involves: (i) replacing what is removed, (ii) restoring what has been degraded, and (iii) responding prudently to off-site effects of management-induced alterations in ecosystem services (e.g. greenhouse gas emission, non-point source pollution and sedimentation) and disservices.

Adoption of NT has its own potential and challenges. Despite more than 50 years of research in temperate and tropical climates, NT farming is adopted on only 124.8 Mha (~ 9% of cropland area). Frustratingly, adoption of NT has been especially low with resource-poor farmers and smallholders in developing countries, where it would otherwise be desperately useful.

Among numerous constraints to the adoption of NT is the competing use of crop residues harvested for cattle feed, cooking fuel, construction, and other domestic and commercial uses. Thus, a market-based approach is needed to promote adoption of NT through economic incentives or performance payments for ecosystem services, which could also reduce disservices or trade-offs. To be effective, however, rational value of a specific ecosystem service (i.e., SOC sequestration) must be objectively assessed. Undervaluing an ecosystem service would jeopardize the finite soil resource and aggravate disservices. No-till farming, conservation agriculture and sustainable land management are proven innovative options that maintain or enhance ecosystem services and reduce risks of disservices. Adoption of NT should be expanded to sustain or improve ecosystem services to meet the needs of a growing world population.

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