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Review

Are Nitrogen Fertilizers Deleterious to Soil Health?

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Abstract: Soil is one of the most important natural resources and medium for plant growth. Anthropogenic interventions such as tillage, irrigation, and fertilizer application can affect the health of the soil. Use of fertilizer nitrogen (N) for crop production influences soil health primarily through changes in organic matter content, microbial life, and acidity in the soil. Soil organic matter (SOM) constitutes the storehouse of soil N. Studies with ^{15}N-labelled fertilizers show that in a cropping season, plants take more N from the soil than from the fertilizer. A large number of long-term field experiments prove that optimum fertilizer N application to crops neither resulted in loss of organic matter nor adversely affected microbial activity in the soil. Fertilizer N, when applied at or below the level at which maximum yields are achieved, resulted in the build-up of SOM and microbial biomass by promoting plant growth and increasing the amount of litter and root biomass added to soil. Only when fertilizer N was applied at rates more than the optimum, increased residual inorganic N accelerated the loss of SOM through its mineralization. Soil microbial life was also adversely affected at very high fertilizers rates. Optimum fertilizer use on agricultural crops reduces soil erosion but repeated application of high fertilizer N doses may lead to soil acidity, a negative soil health trait. Site-specific management strategies based on principles of synchronization of N demand by crops with N supply from all sources including soil and fertilizer could ensure high yields, along with maintenance of soil health. Balanced application of different nutrients and integrated nutrient management based on organic manures and mineral fertilizers also contributed to soil health maintenance and improvement. Thus, fertilizer N, when applied as per the need of the field crops in a balanced proportion with other nutrients and along with organic manures, if available with the farmer, maintains or improves soil health rather than being deleterious.

Keywords: soil organic matter; soil biota; soil acidity; soil erosion; fertilizer management; site-specific nutrient management; balanced use of fertilizers; integrated nutrient management

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1. Introduction

Soil is fundamental to crop production and constitutes a natural resource that provides humans with most of their food and nutrients. However, it is finite and fragile, and requires special care and conservation so that it can be used indefinitely by future generations. Doran and Parkin [1] defined soil quality or soil health as its capacity to function within ecosystem and land-use boundaries, sustain biological productivity, maintain environmental quality, and promote plant and animal health. Soil as a medium for plant growth constitutes a living system and a habitat for many organisms and is characterized mainly by its biological functions, which operate through complex interactions with the abiotic, physical, and chemical environment. Soil health often reflects the condition of the soil in terms of management-sensitive properties and provides an idea of its overall fitness for carrying out ecosystem functions and responding to environmental stresses [2]. According to Kibblewhite et al. [3], a healthy agricultural soil is one that is capable of supporting the production of food and fiber to a level, and with regard to quality, it is sufficient to meet human requirements and can continue to sustain those functions that are essential to maintaining the quality of life for humans and the conservation of biodiversity. This definition implies that soil health is an integrative property that reflects the capacity of the soil to respond to agricultural interventions and circumvent processes that degrade it.

The main driver for anthropogenic interventions in the functioning of soils over the past century has been the quadrupling of the world's population, which has demanded a fundamental change in soil and crop management in order to produce more food from land already in cultivation [4]. Cultivation of soil to prepare the seed bed possibly constituted the first human intervention. In regions receiving little rainfall, irrigation represented another major external influence on the soil. Additionally, during the last 70 years or so, the application of mineral fertilizers has constituted an important human intervention that has influenced the functioning of agricultural soils, although the widespread use of mineral fertilizers has been one of the major factors in ensuring global food security. Every human intervention invariably represents major and sometimes irrevocable change in the nature and properties of the original soil. The key issue is to minimize the negative effects of such changes. Otherwise, the history of agriculture is replete with examples in which civilizations waned or disappeared because of failure to minimize the impact of human interventions on the soil resource.

Mineral fertilizers are applied to the soil to supplement or substitute for biological functions that are considered inadequate or inefficient for achieving the required levels of production. As per FAO's revised projection regarding world agriculture, global agricultural production in 2050 should be 60% higher than in 2005/2007 [5]. To close this gap through agricultural production increases alone, total crop production would need to increase even more from 2006 to 2050 than it did in the same number of years from 1962 to 2006—an 11% larger increase [6]. The bulk of the projected increases in crop production will come from high yields, which normally demand high fertilizer application rates, and will lead to an increase in fertilizer use [5]. According to Erisman et al. [7], over 48% of the more than 7 billion people alive today are living because of increased crop production made possible by applying fertilizer nitrogen (N). However, fertilizers being chemicals can potentially disturb the natural functioning of the soil and may also affect the output of other ecosystem services.

The challenge ahead is to manage fertilizers and soil in such a way that not only food demands are continuously met, but soil also remains healthy to support adequate food production with minimal environmental impact. The objective of this paper is to examine how fertilizer N use affects important and crucial soil health parameters such as soil organic matter (SOM), carbon (C), N, soil microorganisms, and soil acidity. As mineral fertilizers can potentially affect normal functioning of the soil, important management aspects of fertilizer N have also been discussed in terms of supplying adequate amounts of nutrients to crop plants, as well as maintenance of soil health.

2. Fertilizer Use—Soil Health Linkages

The major impact of fertilizers on the soil health and ecosystem functions is regulated through their effect on primary productivity. There are hardly any direct toxic effects even when fertilizers are applied in somewhat excessive quantities; the effects are on rates of different processes in the soil. Prior to the development of Haber-Bosch process in the early 1900s and introduction of N fertilizers around middle of the last century, organic manures (mainly animal manures) containing large amount of organic materials and legume crops used to be the major source of N for crops. An important indirect consequence of the increasing use of N fertilizers was a reduction in the use of organic manures; decoupling of animal farming from arable farming and availability of sewage sludges were also factors in the reduced use of organic manures. Subsequently, after a couple of decades, there was a revival of interest in organic manures due to their increasing supplies and their perceived role in soil health and nutrient recycling. Nevertheless, in several developing countries, particularly in Asia, crop production still relies more on fertilizers because of limited availability of animal manures and crop residues. For example, in South Asia, which accounted for more than 18% of the global fertilizer consumption in 2015 [8], a significant proportion of animal excreta are used as household fuel rather than for making organic manure for crops.

Soil organic matter is a relatively small component of the soil in terms of volume, but it constitutes the single most important soil property in relation to soil health. It exerts profound influence on the chemical, physical, and biological properties of the soil. Rate of decomposition of 'low quality' or high C:N ratio organic inputs and SOM increases when fertilizers, particularly N, are applied to the soil [9]. Fertilizer application increases microbial decomposer activity, which has been limited due to low nutrient concentrations in the organic materials. Thus, application of fertilizer N may lead to accelerated decomposition of organic matter in the soil and adversely affect the soil health.

Soil microbial life and associated microbial transformations constitute another important soil health parameter that may be affected by application of fertilizers. While net primary production in agricultural ecosystems is generally N limited, activity of soil microorganisms may be C and/or N limited [10]. The response of soil microbes to fertilizer N application may, therefore, differ from the response of the plants. That the soil biota are adversely affected due to application of N fertilizers is one of the notions that has been put forth many times to support the argument against fertilizers. However, N fertilizers may lead to increased acidity and adversely affect many soil functions. On the other hand, fertilizer use may reduce soil erosion and may have a positive impact on soil health.

3. Fertilizer Use Effects on Soil Organic Matter

Soil organic matter is a key indicator of soil health because of its vital functions that affect soil fertility, productivity, and the environment. In low-fertility ecosystems, application of nutrients through fertilizers regulates net primary productivity and SOM cycling [11,12]. Build-up of SOM definitely leads to improvement in soil health. However, over time, if the SOM level declines by soil microbial mineralization and/or other losses such as leaching and soil erosion, the soil health deteriorates not only in terms of many benefits including improvement in soil structure, increased soil C storage, and water holding capacity but also N nutrition of crop plants. Because of the fundamental coupling of microbial C and N cycling and the close correlation between soil C and N mineralization, the management practices that lead to loss of soil organic C (SOC) also have serious implications for the storage of N in soil. Thus loss of SOM can be inherently detrimental to crop productivity.

Dourado-Neto et al. [13] conducted a ^{15}N-recovery experiment in 13 diverse tropical agro-ecosystems and estimated the total recovery of one single ^{15}N application of inorganic N during three to six growing seasons. Between 7 and 58% (average of 21%) of crop N uptake (mean 147 $\pm$ 6 kg N ha^{-1}) during the first growing season was derived from fertilizer. On average, 79% of crop N was derived from the soil (Table 1). Average recoveries of ^{15}N-labeled fertilizer and residue in crops after the first growing season were 33 and 7%, respectively. Corresponding recoveries in the soil were 38 and 71%. After five growing seasons, more residue N (40%) than fertilizer N (18%) was recovered in the soil, better sustaining the N content in SOM. Making a worldwide evaluation of fertilizer N use efficiency in cereals, Ladha et al. [14] used data from 93 published studies and concluded that average ^{15}N fertilizer recovery in the grain and straw in maize, rice, and wheat in the first growing season was 40, 44, and 45%, respectively. Overall recovery based on ^{15}N dilution method among regions and crops was 44% (572 data points). The International Atomic Energy Agency [15] reported that the average percentage of single applications of ^{15}N fertilizer recovered in above-ground portion of the crop plants in the subsequent five growing seasons (excluding the crop to which ^{15}N fertilizer was applied) across all locations was 5.7 to 7.1%. Thus, with an average ^{15}N fertilizer recovery of 44% in the first crop of a cropping system [14], the total recovery of ^{15}N fertilizer in the first and the five subsequent crops is approximately 50%. Assuming that amount of ^{15}N in the roots becomes negligible in the sixth growing season, large portion of remaining 50% of the ^{15}N fertilizer will become part of the large soil N pool and some portion may get lost from the cropping system [16]. Thus, N bound to C in the SOM is not only the largest source of N for the crop plants but also the largest sink of N fertilizer inputs in modern cereal cropping systems, so that SOC impacts both crop yield and N losses to the environment.

Table 1. Total above-ground N accumulation and contribution of fertilizer N and soil N as estimated by applying ^{15}N labelled fertilizers for crops grown under diverse soil and climatic conditions.

Country	Soil Order	Crop	Fertilizer N Applied (kg N ha^{-1})	Total Crop N (kg N ha^{-1})	Derived from Fertilizer N (%)	Derived from Soil N (%)
Bangladesh	Haplaquepts	Wheat	60	60 ± 3	43 ± 1	57 ± 1
Brazil	Ultisol	Sugarcane	63	251 ± 7	16 ± 1	84 ± 1
Chile	Andisol	Maize	300	178 ± 7	31 ± 2	69 ± 2
Chile	Andisol	Wheat	160	124 ± 4	16 ± 2	84 ± 2
China	Inceptisol	Rice	60	292 ± 7	7 ± <1	93 ± <1
Egypt	Entisol	Wheat	60	80 ± 6	20 ± 1	80 ± 1
Malaysia	Ultisol	Maize	60	53 ± 2	23 ± 1	77 ± 1
Morocco	Aridisol	Wheat	42	161 ± 7	18 ± 1	82 ± 1
Morocco	Inceptisol	Sunflower	35	129 ± 7	7 ± <1	93 ± <1
Morocco	Inceptisol	Bean	85	225 ± 6	7 ± <1	93 ± <1
Sri Lanka	Ultisol	Maize	60	139 ± 6	11 ± <1	89 ± <1
Sri Lanka	Ultisol	Maize	60	139 ± 6	18 ± 1	82 ± 1
Vietnam	Ultisol	Maize	120	92 ± 3	58 ± 1	42 ± 1
		Mean		147 ± 6	21 ± 1	79 ± 1

Modified from Dourado-Neto et al. [13].

Plant uptake of native soil N is boosted either through increase in mineralization of soil N or by plant-mediated processes such as increased root growth and rhizosphere N priming [17,18]. Native soil N priming dynamics are influenced by soil type, fertilizer type, and environmental factors [19–21]. Using a meta-analysis based on 43 ^{15}N studies from all over the globe, Liu et al. [22] revealed fertilizer N effects on mineralization and plant uptake of native soil N were not influenced by study type (laboratory or field), location and duration, soil texture, C and N content, and pH. Although fertilizer tended to increase N priming through variable effects on native soil N mineralization, plant uptake of native soil N increased consistently. This inconsistency suggested that there exists a complex interaction between fertilizer N addition and microbial immobilization-mineralization of N and C, but not that fertilizer N application results in loss of SOM.

Potentially, fertilizer N application can affect SOM in two ways: (i) it may increase SOM by promoting plant growth and increasing the amount of litter and root biomass added to soil compared with the soil not receiving fertilizer N; and (ii) it may accelerate SOM loss through decay or microbial transformation of litter (leaves, straw, manures) and indigenous forms of organic C already present in the soil [9]. The first mechanism is widely accepted, but the second mechanism has not been demonstrated indisputably. Normally, SOM decreases with cultivation [3,23,24] when no N fertilizer is applied. Application of fertilizer N often increases SOM level and C sequestration in soils of intensively managed multiple cropping systems [25–30]. Ghimire et al. [26] have cited a number of long-term fertility experiments from India and Nepal in which SOC in control plots after 20 years ranged from 1.9 to 7.3 g kg^{-1}, but in all the experiments application of optimum N, P and K fertilizers registered an increase in SOC over control ranging from 0.2 to 3.5 g kg^{-1}. Also, fertilizer use could promote aggregate formation [31] and stabilization [32], and enhance the spatial inaccessibility for decomposing organisms [33].

Poffenbarger et al. [34] evaluated changes in surface SOC over 14 to 16 years by applying fertilizer N rates empirically determined to be insufficient, optimum, or excessive for maximum maize yield. It was observed that SOC balances were negative when no N was applied. For continuous maize, the rate of SOC storage increased with increasing N rate, reaching a maximum at the optimum N rate but decreasing above the optimum N rate. When fertilizer N application rate was below the optimum, applied N stimulated crop growth, leading to increasing crop residue inputs to the soil and, in turn, increasing the rate of soil organic storage. However, when the N application rate was above the optimum, added N did not increase crop residue production beyond that observed at the optimum level but increased residual inorganic N, which enhanced SOC mineralization leading to loss of SOC. Green et al. [35] also observed that annual additions of more N than needed to maximize yields of maize could cause losses of SOM and suggested that reducing unnecessary fertilization could help conserve

SOM. Conceptual understanding of the SOC response to N fertilization is illustrated in Figure 1 [34]. Residual soil inorganic N produced due to application of fertilizer N beyond the optimum level may enhance mineralization of SOC by eliminating N limitation on microbial growth [35,36] or by adversely affecting soil aggregation [37,38], which makes previously protected SOM more susceptible to decay. Excessive N fertilization may also decrease the C:N ratio of crop residues [39] and enhance their decomposition rate. There may be multiple processes controlling the SOC response to N fertilization, but the extent of increased C inputs vis-à-vis SOC mineralization depends on the N sufficiency level.

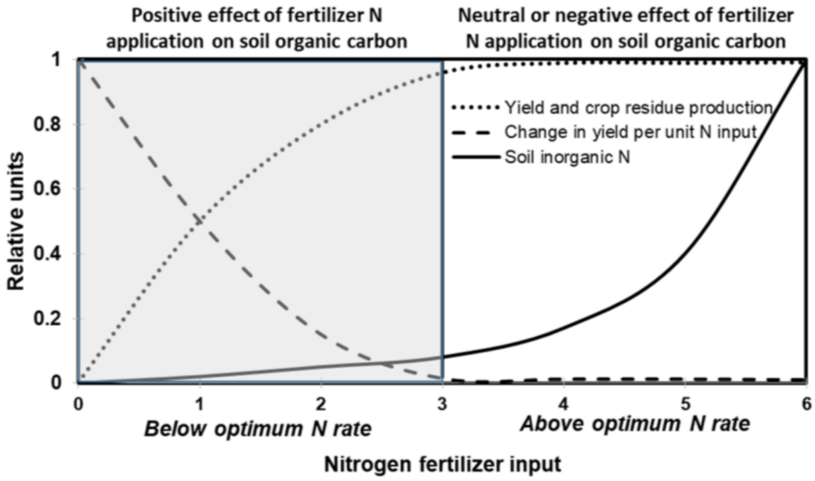

Figure 1. Conceptual diagram showing possible effects of fertilizer application to crops on SOC as defined by relationships between increasing fertilizer N application levels and (i) yield and crop residue production, (ii) change in yield per unit N input, and (iii) residual soil inorganic N. Maximum yield of the crop is obtained at the optimum N rate. Expected SOC responses to fertilizer N application below and above optimum N rate are shown above the grey and white areas of the plots, respectively (Modified from Poffenbarger et al. [34]).

Glendining and Powlson [40] found that in 84% comparisons in 45 long-term experiments in temperate regions, applications of fertilizer N on long-term basis increased total soil organic N (SON) as compared to in the treatments receiving no fertilizer. However, Khan et al. [41] and Mulvaney et al. [36] reported that in long-term experiments located in both temperate and tropical regions, continuous application of fertilizer N induced a net loss of SOC in 73% sites and reduction in soil N at 92% of the sites examined. Powlson et al. [42] argued that data sets used by these authors were not comprehensive enough, and long-term changes in soil N and C in the zero-N control plots were not taken into consideration. Ladha et al. [43] resolved this controversy using data from 135 studies of 114 long-term experiments located at 100 sites located all over the world. The data pertaining to SOC and SON were analyzed following time-response ratio and time by fertilizer N response ratio. The time-response ratio is a percentage change in total SOC or N compared with the initial amount, and it was calculated separately for both zero-N and N-fertilized treatments. Khan et al. [41] and Mulvaney [36] used this approach, and like them Ladha [43] also observed an average decline in SOC to the tune of 16% and 10% in zero-N and fertilizer N amended plots; corresponding decline in SON was 11% and 4% (Table 2). These decreases were confounded with decrease in SOM content occurring independently of the use of fertilizer N. Ladha et al. [43] separated the two processes by following the change over time in SOM content with or without fertilizer, and this was done by analyzing the data using time by fertilizer N response ratio. While the time-response ratio addressed the impact of the whole system (tillage, residue management, erosion, fertilizer amendment) on changes in SOC or SON, the time by fertilizer N response ratio specifically assessed the impact of fertilizer N amendment, and it is defined as the percentage difference between the change in SOC or N in the N-fertilized treatments compared with the changes in zero-N treatment. Using the time by fertilizer ratio, which is based on changes in the paired comparisons at the initiation of the long-term experiments and final sampling period, Ladha et al. [43] observed overall averages of 8% higher SOC and 10% higher SON with fertilizer N than with zero-N (Table 2). Furthermore, the positive effect of fertilizer N in tropical, humid subtropical, and temperate soils ranged from 3 to 16% for SOC and 8 to 15% for SON, with the highest increases observed in the tropical environment (Table 2). Due to inherently lower status of SOC and N than in temperate soils, the relatively higher positive effect of fertilizer N application is expected in tropical soils. Recently, Geiseller and Scow [44] and Körschens et al. [45] also observed that in long-term experiments from all over the world, application of mineral fertilizers leads to increase in SOM as compared to in no-fertilizer plots (Table 3). Using total organic C and natural ^{13}C abundance measurements in a long-term experiment under continuous maize, Gregorich et al. [46] observed that fertilized soils had more organic C than unfertilized soils; the difference was accounted for by more C4-derived C in the fertilized soils.

Table 2. Changes in SOC and SON in zero-N and N fertilized plots observed by meta-analysis of data from 114 long-term experiments following time-response ratio (TR) and time by fertilizer N response ratio (TNR).

	% Change in SOC		% Change in SON	
	Zero-N	Fertilizer N	Zero-N	Fertilizer N
TR: overall changes	−16	−10	−11	−4
TNR: overall changes	-	8	-	10
TNR: changes in tropical soils	-	16	-	15
TNR: changes in humid tropical soils	-	11	-	11
TNR: changes in temperate soils	-	3	-	8

Data source: Ladha et al. [43].

Table 3. Increase in SOC due to fertilizer application as compared to in the unfertilized controls in meta-analysis conducted on long-term experiments from all over the world.

Crops	Region	Duration of Long-Term Experiments (years)	Increase in SOC (%)	Reference
Non-lowland rice crops	World	5–130	12.8	Geiseller and Scow [44]
Cereal crops	World	6–158	8	Ladha et al. [43]
Wheat, barley, oats, sugar beets, potato, maize, sorghum, rye	Europe	16–108	10	Körschens et al. [45]

The North Indian state of Punjab is the most intensively cultivated region in India, with a cropping intensity of 190%, predominantly of a rice–wheat cropping system. A study based on 0.319 million soil samples of the 0–20 cm plough layer analyzed during 25 year period between 1981/82 to 2005/06 revealed that as a weighted average for the whole state, SOC increased from 2.9 g kg^{-1} in 1981/82 to 4.0 g kg^{-1} in 2005/06, an increase of 38% [47]. A close relationship (R^2 = 0.79) between SOC stocks in the plough layer and total rice and wheat grain yield during the 25-year period was observed. Increased productivity of rice and wheat resulted in enhanced C accumulation in the plough layer by 0.8 t C ha^{-1} t^{-1} of increased grain production. The increased productivity of both rice and wheat in the Punjab was achieved through increasing fertilizer (N, P, and K) use from 0.762 Mt in 1980/81 to 1.687 Mt in 2005/06 or from 112.5 kg ha^{-1} in 1980/81 to 214.0 kg ha^{-1}. Soil pH declined by 0.8 pH units from 8.5 in 1981/82 to 7.7 in 2005/06. This pH decline has positive implications for availability of P and micronutrients such as Zn, Fe, and Mn. Tian et al. [48] conducted a meta-analysis of paired-treatment data from 95 long-term field experiments published from 1980 to 2012 to characterize the changes in SOC in paddy soils in China. While significant increase in the SOC was observed in the optimum fertilizer N, P, and K fertilizer treatment as compared to in the no-fertilizer treatment; the mean difference in SOC change rates between the two treatments was measured to be 0.140 ± 0.023 g kg^{-1} $year^{-1}$. Using a meta-analysis based on 257 published studies, Lu et al. [49] revealed that despite increased soil respiration, there was a significant 3.5% increase in C storage in agricultural ecosystems due to application of N. The N-induced change in soil C storage was related to changes in below-ground production rather than above-ground growth. Russel et al. [39] also observed that quantity of below-ground organic C inputs was the best predictor of long-term soil C storage. Shang et al. [50] conducted a meta-analysis based on published data on crop yields and soil parameters from long-term experiments in maize-wheat, rice-rice, and rice-wheat cropping systems in China. Although conservation of SOC in upland maize-wheat system was conspicuously less than in the rice based cropping systems, application of optimum rate of N, P, and K fertilizers resulted in build-up of SOC over no-fertilizer control in all the three cropping systems (Table 4). Decrease in SOC content in the no-fertilizer control from the initial values in the completely aerobic maize-wheat cropping system should be due to cultivation of the soil.

Table 4. Average SOC content at the start (initial) of long-term experiments on maize-wheat, rice-wheat, and rice-rice cropping systems and in no-fertilizer (N, P, and K) control and optimum N, P, and K fertilizer level treatments at the end of the experiments in different locations in China.

Cropping System	Number of Experiments	Duration (years)	SOC (g kg^{-1})		
			Initial	No-Fertilizer Control	Optimum N, P and K Fertilizer Levels
Maize-wheat	12	6–25	6.4	5.8	6.8
Rice-wheat	10	9–27	14.3	14.9	16.3
Rice-rice	23	6–26	16.7	18.1	19.6

Data Source: Shang et al. [50].

Cultivation invariably reduces SOM levels to an extent that depends on management and inputs. In well managed cultivated soils, SOC fluctuated between a low steady state value of SOM in the heavily cultivated soil and the highest value observed in the uncultivated soil [51]. Cultivation of the soil leads to lower equilibrium soil C levels, but the addition of fertilizers reduces the extent of SOM decline observed with cultivation. Katyal et al. [52] critically analyzed data from several long-term fertility experiments in India and documented such changes. Twenty years after initiation of a long-term experiment in a virgin soil, SOM content in the no-fertilizer control reached 34% of the initial value and seemed to have stabilized at a lower equilibrium level as defined by Buyanovsky and Wagner [51]. Loss in SOM was obviously due to cultivation of the virgin soil. Buyanovsky and Wagner [51] reported a decline in native organic matter between 20 and 40% within 5 years after opening of virgin land. However, when optimum level of fertilizers was applied, SOM remained stable over the first decade, but in the next 3 years fell to about 40% of the initial value. In contrast to a virgin soil, already cultivated soil implies that the soil had already shifted to a new dynamic equilibrium but had probably not yet reached the steady state low value of SOM in the heavily cultivated soil. In long-term experiments initiated in soil already under cultivation, SOM declined without any fertilizer application. However, SOM levels were either maintained or increased when adequate amount of N, P, and K fertilizers was applied [52]. This conclusion was valid, irrespective of the location or the cropping system. That soil health in terms of SOC and SON declines when soil is tilled year after year is now an established fact [3,23,24]. Therefore, interaction between tillage and fertilizer use should be taken into account when interpreting changes with time in the SOM in long-term experiments.

4. Effect of Fertilizer Use on Microbial Life Ion the Soil

Several ecosystem services or the beneficial functions provided by soil are driven by many interrelated and complex biological processes. The concept of soil health takes into account not only the soil biota and the myriad of biotic interactions that occur, but also considers that the soil provides a living space for the biota. Microorganisms and various by-products of their metabolism play an important role in the formation of soil aggregates and in soil structure maintenance. Since soil constitutes an open system, its integrity or health is affected by external environmental and anthropogenic pressures. Recently, Hermans et al. [53] observed that soil bacterial communities and their relative abundances varied more in response to changing soil environments than in response to changes in climate or increasing geographic distance. As microorganisms play an important role in maintaining fertile and productive soils, the effect of fertilizers on microbial communities has potentially important implications for sustainable agriculture. Applied nutrients constitute a controlling input to the soil system and the processes within it, but adequate knowledge is lacking about the impacts of nutrient additions on the condition of different assemblages of soil organisms. According to O'Donnell et al. [54], fertilizers do affect microbial community structure, but the relationship between diversity, community structure, and function remains complex and difficult to interpret using currently available chemical and molecular fingerprinting techniques. Mineral fertilizers interact with microbial communities in the soil in a number of ways and affect the population, composition, and function of soil microorganisms [55]. These may promote growth of microbes directly by providing nutrients and indirectly by stimulating plant growth and enhancing root C flow [56]. However, fertilizers, particularly N, when applied to soil may result in soil acidification limiting microbial growth and activity in soils [57]. Several studies conducted during last 2–3 decades have revealed that fertilizer application usually favours the accumulation of bacterial residues [58] and increases soil microbial biomass [59–63]. In some studies, fertilizer application increased biomass C and N [64–66]. Significant improvement in soil quality in terms of increased SOC and soil microbial biomass due to long-term application of fertilizers in maize–wheat cropping systems has been reported by Li et al. [67] and Liu et al. [68].

Mbuthia et al. [69] observed that fertilizer N application to cotton continuously for 31 years significantly increased soil microbial biomass N, mycorrhizae fungi biomarkers, b-glucosaminidase (N-cycling) activity, and basal microbial respiration rates. In a study in which inorganic fertilizers were continuously applied for 13 years to flooded double rice crop, Zhong and Cai [70] found that stimulation of microbial biomass and community functional diversity by fertilizer N could be achieved only after improvement of the P supply. However, most microbial parameters were correlated with SOC content, indicating that the application of nutrients through fertilizers affected microbial parameters in the soil indirectly by increasing the accumulation of SOM. It is generally considered that the primary limiting factor for microbial activity in soils is the availability of C substrate. However, soil microbes may frequently be limited by the supply of N in the soil [71]. When demand for N exceeds its supply, the functional capacity of the soil system is strongly influenced by N availability. Under such situations in agro-ecosystems, soil health declines without additional inputs of N via fertilizers or organic manures, and particularly without due consideration of the associated C requirements of the biomass [37].

Effect of fertilizer application on the soil biota can be positive or negative and vary in duration, depending upon the type and amount of fertilizer used and mode of application. For example, potential damage to soil microorganisms from high concentration of ammonia fertilizer applied in bands is usually short-term, and only in the zone of application. Angus et al. [72] reported that injection of urea and ammonia in bands generally exhibited a short-term effect on microbial activity in the soil. Total microbial activity was reduced in narrow bands of application for a period of 5 weeks, after which levels returned to normal. However, an 80% reduction in the number of protozoa did not return to normal after 5 weeks. On the other hand, there was a large increase in the number of nitrifying bacteria in the soil 5 weeks after application of urea/ammonia in bands. Geiseller and Scow [44] carried out a meta-analysis based on 107 data sets from 64 long-term experiments from around the world and revealed that application of mineral fertilizers resulted in a significant increase (15.1%) in the microbial biomass above levels in the no-fertilizer control treatments. Where soil pH was 7 or higher, the fertilizer induced increase in microbial biomass averaged 48%, but fertilizer application tended to reduce microbial biomass in soils with a pH below 5 (Table 5). Furthermore, the increase in microbial biomass was the highest in experiments that were in place for at least 20 years. Biederbeck et al. [73] also reported little impact on soil microbial populations when urea and anhydrous ammonia were applied continuously for 10 years. The arbuscular mycorrhizal fungi biomass was increased by application of N and P fertilizer in the N- and P-deficient sites, respectively [74].

Table 5. Unweighted averages of soil microbial biomass C (mg kg^{-1}) in fertilizer N (+N) and no-N treatments in 64 non-lowland rice long-term experiments from all over the world.

	Number of Data Sets	Soil Microbial Biomass C (mg kg^{-1})	
		no-N	+N
All data sets	107	238	268
pH in +N treatment: <5	17	240	213
pH in +N treatment: 5–7	39	234	253
pH in +N treatment: 7 or higher	17	139	205
Duration of long-term experiment: 5–10 years	18	300	239
Duration of long-term experiment: 10–20 years	34	227	270
Duration of long-term experiment: 20 years or longer	55	224	276

Modified from Geiseller and Scow [44].

That tilling of soil leads to decline of its health is also revealed by changes in microbial community structure assessed using phospholipid fatty acid analysis and automated ribosomal intergenic spacer analysis [75,76]. In a study conducted by Doran [77], microbial biomass and potentially mineralizable N levels of no-tillage soils averaged 54% and 37% higher, respectively, than those in the ploughed soils. In a meta-analysis based on 139 observations from 62 studies, Zuber and Villamil [78] inferred that microbial biomass and enzyme activities were greater under no-till as compared to in the tilled soils. Therefore, in conventionally tilled fertilized soils the reduced microbial activity is due to cultivation of soils rather than the effect of fertilizer application.

Over-use of mineral fertilizers and excessive tillage can affect biological communities in the soil by damaging their habitats and disrupting their functions [37]. Over-use of fertilizer, particularly N, is like enrichment of ecosystems with reactive N. Using a meta-analysis based on 82 published field studies, Treseder [79] reported that microbial biomass declined 15% on average under heavy N fertilization, but fungi and bacteria were not significantly altered in studies that examined each group separately. Declines in abundance of microbes and fungi were more evident in studies of longer durations and with higher total amounts of N added.

5. Potential Contribution of Nitrogen Fertilizers to Soil Acidity

Nitrogen fertilizers can exert indirect negative effects on soil health arising through lowering of soil pH due to natural transformations of N in the soil. Soil pH is one of the most influential factors affecting the microbial community in soil. As shown in Table 5, while fertilizer-induced increase in microbial population in long-term experiments was observed at soil pH 7 or higher, a reduction in microbial biomass was observed in soils with a pH below 5. In a silt loam soil on which barley has been continuously grown for more than 100 years, Rousk et al. [80] observed a fivefold decrease in bacterial growth and a fivefold increase in fungal growth due to lowering of pH from 8.3 to 4.0.

Form of fertilizer N applied (NO_3^-, NH_4^+, urea), fertilizer product type (for example, ammonium nitrate, calcium ammonium nitrate), the net balance between proton-producing and consuming processes, and the buffering capacity of the soil dictate the extent of soil acidification due to application of fertilizer N. Buffering capacity of the soil as determined by the presence of solid-phase calcium carbonate resists change in soil pH due to N transformations [81]. In arid and semi-arid areas of the world, soils are generally calcareous and thus highly buffered. In temperate regions, soils are generally neutral or slightly acidic in reaction, whereas tropical soils are usually highly weathered and generally acidic with little or no buffering capacity. During the acidification process, base cations such as calcium and magnesium are released from the soil. With continued addition of fertilizer N, the base cations get depleted and aluminum (Al^{3+}) is released from soil minerals, often reaching toxic levels that induce nutrient disorders in plants. Guo et al. [82] reported severe soil acidification in large crop production areas in China following application of high fertilizer N rates between the 1980s and 2000s. Based on strictly paired data available from 154 agricultural fields, top soils were significantly acidified with an average pH decline of 0.50. Fertilizer N application released 20 to 221 kg hydrogen ion (H^+) ha^{-1} $year^{-1}$, and base cations uptake contributed a further 15 to 20 kg H^+ ha^{-1} $year^{-1}$ to soil acidification. In Southern China, Lu et al. [83] observed that after application of ammonium nitrate for 6 years, the site was showing high acidification [pH(H_2O) < 4.0], negative water-extracted acid neutralizing capacity, and low base saturation (<8%) throughout soil profiles.

6. Rational Use of Fertilizers Enhances Soil Health by Reducing Soil Erosion

Role of anthropogenic activities in causing soil erosion is very well documented [84], but the connection between erodibility of the soil (defined as the susceptibility of a soil to become detached and transported by wind, water, or ice) and crop production practices, especially the use of fertilizers, is not well documented. Soil erosion is a problem when there is insufficient ground cover to protect the soil and reduce the impact of rainfall and wind on the soil surface and when aggregate stability is reduced due to limited SOC. Adequately fertilized crops will have extensive root system and top growth. A well-developed canopy reduces the pounding effect of water drops from rain so that runoff is reduced and erosion is minimized. Also, extensive root system developed in the well fertilized soil helps hold soil in place and decreases the potential for soil loss in runoff water. Bhattacharyya et al. [85] reported reduced loss of soil due to erosion by applying fertilizers to crops as compared to when no fertilizer was applied. At 2% slope, soil loss by erosion was reduced by 7.2% and 11.7% by applying fertilizer to sorghum (*Sorghum bicolor*) and chickpea (*Cicer arietinum*), respectively. According to Portch and Jin [86], balanced fertilization of crops in China could reduce soil erosion. They further reported that work conducted by International Board for Soil Research and Management (IBSRAM) in late 1980s in several Asian countries showed that fertilizer use alone could reduce soil erosion from 50 to 15 t ha^{-1} $year^{-1}$. Biological N fixation and manure recycling are the only local nutrient sources that are not always optimally exploited. The inability to match crop harvests with sufficient nutrient inputs leads to depletion of nutrients and SOM, declining soil health, and increased risk of land degradation through erosion.

7. Optimizing Fertilizer Management to Maintain Soil Health

A sustainable agricultural production system with good soil health having the capacity to produce high yields with fewer external nutrient inputs can be developed using the correct combination of ecosystem processes and appropriate use of fertilizers. Soils in agro-ecosystems should be able to supply a certain minimum level of plant-available N and other essential nutrients at different growth stages of crop plants. In principle, the concept of optimum fertilization aims at a dynamic balance between nutrient requirement to obtain high yields and nutrient uptake by crops. This is achieved by maintaining synchrony between nutrient demand of the crop and the supply of nutrients from all sources including fertilizer and soil throughout the growing season of the crop.

Application of optimum doses of all nutrients is important, but due to fundamental coupling of C and N cycles, optimization of fertilizer N management is more closely linked to build-up of SOC and soil health. Concepts emerging from the work of Poffenbarger et al. [34] and depicted in Figure 1 suggest that when N inputs are below the optimum rate at which maximum yield is obtained, applied N stimulates crop growth, increasing crop residue inputs to the soil and thereby increasing SOC. Additionally, when fertilizer N inputs are above the optimum level, added N imparts no change in crop residue production but increases residual inorganic N, which alleviates microbial N limitation and thereby enhances mineralization of SOC [35]. However, crop response to N fertilization is site-specific because there exists large spatial and temporal variability in soil N supply, which is in part due to historical differences in management. Regional blanket fertilization recommendations cannot account for this variability. Thus, site-specific nutrient management strategies based on principles of synchronization of crop N demand with N supply from all sources including soil and fertilizer N can ensure high yields along with maintenance of soil health. These can not only account for site-to-site variability in optimum fertilizer rate but also resolve uncertainty regarding response of SOC build-up to fertilizer application.

In the last two decades, site-specific real-time methods of N management that utilize crop simulation models, remote sensing, or on-the-go crop sensing/variable-rate N spreaders to determine the spatially variable needs for N at critical growth stages are increasingly being used to apply optimum doses of fertilizer N to crops following synchrony principles. Whether implemented for crops in small fields with little or no mechanization in developing countries or practiced as precision agriculture for variable rate adjustment using on-the-go canopy reflectance spectra in large fields of developed countries [87], the principles and objectives of site-specific N management are the same.

The first report of the Status of the World's Soil Resources prepared by the Intergovernmental Technical Panel on Soils lists nutrient imbalances (both nutrient deficiency and nutrient excess) as one of the specific threats to soil functions [88]. In a long-term field trial with spring barley, Johnston et al. [89] demonstrated that the grain yield increased by more than 50% with the same amount of fertilizer N only when the plants were grown on a soil well supplied with K. Similarly, barley cultivated on a P-deficient soil yielded only half of the crop, which was grown on a soil with adequate P, although receiving the same amount of fertilizer N. Haerdter and Fairhurst [90] showed that the recovery of N from fertilizers increased from 16% at traditional N and P fertilization levels to 76% at balanced application of N, P, and K fertilizers. Kumar and Yadav [91] reported higher SOM content in plots in which N, P, and K were applied in a balanced proportion on a long-term basis than in treatments receiving only N or inadequate amounts of P (Figure 2). Similarly, Belay et al. [92] observed more SOC and soil microbial biomass in the N, P, and K fertilizer treatment rather than in N, P, or K alone fertilizer treatments in a long-term field experiment on maize-field pea rotation initiated in 1939 in South Africa.

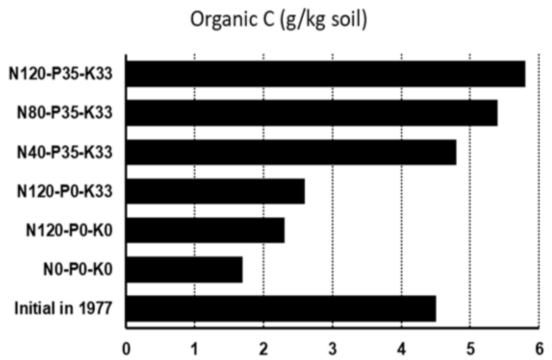

Figure 2. Effect of application of different combinations of N, P, and K fertilizers to rice–wheat cropping system for 20 years on organic C content in the soil in a long-term experiment at Faizabad, India. The numbers after N, P, and K indicate kg ha^{-1}. Data source: Kumar and Yadav [91].

In a 16-year long-term field experiment, Chu et al. [93] observed that balanced application of N, P, and K fertilizers had a higher microbial biomass and activity than in the P- and N-deficient treatments. Balanced fertilization resulted in higher dehydrogenase activity than under nutrient-deficiency fertilization. In a 33-year long-term experiment in a brown soil in China, long-term N and P, as well as N, P, and K, fertilizer application treatments exhibited greatly increased soil microbial biomass C and dehydrogenase activity compared to in the only N treatment [94]. Similarly, in a 21-year long-term experiment, Zhong et al. [95] observed that balanced fertilization with N, P, and K promoted the soil microbial biomass, activity, and diversity and thus enhanced soil health, crop growth, and production. In a wheat-maize cropping system in a fluvo-aquic soil in the North China Plain, Gong et al. [27] reported that balanced application of N, P, and K fertilizers for 18 years showed higher C and N contents of the light and heavy fractions, as well as more culturable microbial counts, than in unbalanced N and P, P and K, or N and K fertilizer treatments.

8. Integrated Management of Fertilizers and Organic Manures for Improvement of Soil Health

With increasing awareness about soil health and sustainability in agriculture, organic manures have regained importance, because these can supply precious organic matter, along with many different nutrients, including micronutrients to the soil. Organic manures also influence the availability of plant nutrients in the soil for plants by changing both the physical and biological characteristics of the soil. The concept of integrated management of mineral fertilizers and organic manures became the mainstay of soil fertility management practices at the turn of the 20th century, because it strives to maintain/improve the fertility and health of the soil for sustained crop productivity on a long-term basis [96]. Nutrients supplied through fertilizers are used to supplement those supplied by the different organic sources available to farmers. In Sub-Saharan Africa, where the traditional farming systems depend primarily on mining soil nutrients, the concept of integrated soil fertility management based on the use of mineral fertilizers, organic inputs, and improved germplasm, combined with the knowledge of adapting these practices to local conditions, has been introduced to intensify agriculture. Fertilizers constitute an entry point for practicing integrated soil fertility management, which is a field-specific strategy for increasing productivity, improving soil health, and a sustainable cropping system [97].

In several long-term experiments initiated in 1970s with different cropping systems in various agro-climatic zones in India, along with several other treatments, the two consisted of application of optimum level of N, P, and K fertilizers with and without farmyard manure. Soil organic C in different treatments estimated at the initiation of the experiments and 20 years later is shown in Table 6. The data convincingly proves that integrated management of mineral fertilizers and farmyard manure resulted in build-up of SOC more than in the fertilizer only treatment. Nevertheless, as already discussed, application of optimum levels of N, P, and K fertilizers resulted in accumulation of SOC more than in the control treatment to which neither fertilizer nor manure was applied. In recent years, several other workers [27,29,32,98–102] have reported that the application of organic manures along with mineral fertilizers increases SOM and different fractions of SOC more effectively than the application of mineral fertilizers alone. Integrated management of organic manures and mineral fertilizers rather than application of fertilizers alone not only has a positive impact on build-up of SOC but also on soil health related microbial indicators like soil microbial biomass, soil bacterial community diversities, and soil enzyme activities [67,103,104].

Table 6. Changes in SOC due to application of optimum N, P, and K fertilizer levels with and without farmyard manure for 20 years to different cropping systems in long-term experiments established in different soil types in India.

Cropping System	Location	Soil	SOC at Initiation (%)	SOC after 20 Years (%)		
				Control	N, P and K Fertilizers	N, P and K Fertilizers + Farmyard Manure
Rice-rice	Bhubaneshwar	Inceptisol	0.27	0.41	0.59	0.76
Rice-wheat	Pantnagar	Mollisol	1.48	0.50	0.95	1.51
Rice-wheat	Faizabad	Inceptisol	0.37	0.19	0.40	0.50
Rice-wheat-jute	Barrackpore	Inceptisol	0.71	0.42	0.45	0.52
Rice-wheat-cowpea	Pantnagar	Mollisol	1.48	0.60	0.90	1.44
Maize-wheat	Palampur	Alfisol	0.79	0.62	0.83	1.20
Rice-wheat	Karnal	Alfisol	0.23	0.30	0.32	0.35
Cassava	Trivandrum	Ultisol	0.70	0.26	0.60	0.98

Data source: Nambiar [105], Swarup et al. [106].

In Sub-Saharan Africa, two types of soils have been recognized in terms of responsiveness to mineral fertilizers. One type of soils are termed as responsive soils, because, due to nutrient mining, crops grown in these soils respond to fertilizer application in a normal way. The other type of soils are referred to as poor, less-responsive soils because these are highly degraded in terms of both extensive nutrient mining and loss of SOM, and crops grown in these respond to fertilizer use minimally or do not respond [107]. The degradation of soil to non-responsive state occurs due to discontinuous, insufficient, or no fertilizer application over a certain period of time. When a certain threshold of soil degradation is exceeded, this condition may not be reversible and soils may not respond immediately to fertilizer or organic manure application so that crop productivity may not return to the level attained before fertilizer use was discontinued. In a study conducted by Zingore et al. [108], response to fertilizer application on less-responsive soils was observed only after application of 17 t ha^{-1} $year^{-1}$ of farmyard manure during three consecutive years. Once the soil became responsive to fertilizers, improvement in agronomic efficiency and soil health could be achieved through integrated nutrient management of fertilizers and farmyard manure. This unique interaction of organic manures and fertilizers seems to be very valuable in dealing with soils degraded due to long history of nutrient depletion.

9. Conclusions and Policy Implications

Nitrogen fertilizers, when applied at rates less than the optimum at which maximum yields are obtained, stimulate crop growth, leading to increasing crop residue inputs to the soil and, in turn, increasing the rate of soil organic storage. Until and unless fertilizer N acidifies the soil to pH < 5, the application of fertilizer at optimal rate generally has a positive effect on soil biota. The balanced application of N, P, and K fertilizers results in further significant improvement in the soil health in terms of increased SOC and soil microbial biomass. The uptake of N by crop plants is generally greater from native soil N than from N applied as fertilizers. As a decline in SOM following the application of fertilizer N is not a general phenomenon, a spiral of decline in soil functioning and crop productivity due to fertilizer N use is not expected. Application of fertilizers more than the optimum level can not only adversely influence biological communities in the soil but may also result in increased residual inorganic N, which can enhance SOC mineralization and loss of SOC. Because there exists large spatial and temporal variability in soil N supply, crop response to N fertilization is site-specific. Thus, site-specific nutrient management strategies based on principles of synchronization of crop N demand with N supply from all sources including soil and fertilizer N hold great potential for ensuring high yields of crops along with maintenance or improvement in soil health.

Soil and agronomic research reviewed and analysed in this paper shows that sustainable agricultural intensification through application of fertilizer N and healthy soils are compatible goals. The extent to which fertilizer N can contribute to economic and efficient crop production, and concomitantly benefit the soil in terms of quality or health, is dictated by the adoption of management practices that ensure that fertilizer N is not applied indiscriminately to agricultural crops. Fertilizer N should never be applied in amounts greater than what is required to obtain optimum yields. Ideally, fertilizer N should be managed on a site-specific basis, whether based on the nutrient status of soil or plants in a given field, so that N is applied in the right amount and at a right time according to the needs of the soil-plant system. The application of fertilizer N in a balanced proportion with other nutrients and integrated nutrient management based on organic manures and fertilizers can lead to further improvements in soil health.

The effect of temperature and moisture on SOM decomposition is very well documented in the literature. However, hardly any studies are available in which the interaction effects of fertilizer N and temperature and moisture on SOM decomposition are reported. This information is needed to evaluate the effect of fertilizer use on soil health under different temperature and moisture regimes. While studies related to soil health and fertilizer N are being reported from different climatic regions of the world, models can be usefully employed to define the specific effects of rainfall or soil moisture and soil temperature on fertilizer N-related soil health issues. The response of different microbial groups to repeated applications of fertilizer N varies and depends on environmental and crop management-related factors. As enough data are not available to understand the interactions among environmental factors, fertilizer N rates and types, and specific groups of soil microorganisms, there is a need to conduct studies to understand these complex interactions. Also, there is a need for adequate documentation of the effect of fertilizer N on the stability of SOM and the fate of organic residues in the long-term in different cropping systems. Long-term agronomic experiments involving the application of fertilizers in different agro-ecological zones across the world can be used to generate information on these lines. Increased soil salinity due to application of mineral fertilizers can deteriorate soil health, but N fertilizers based on sodium salts are no longer applied to field crops. In the quest to reduce the cost of cultivation and possibly maintain and/or improve soil health, in many parts of the world conservation agriculture systems are being adopted. In these systems, soil is tilled to a minimum extent and crop residues are retained in the soil so as to help build up of SOM. There is a need to establish appropriate fertilizer management strategies in such systems so that soil health is maintained or improved.

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